E.S. Cornwall Memorial Scholarship
First Quarterly Report

Research and Development Microgrids and Distributed Generation
Genova, Italy

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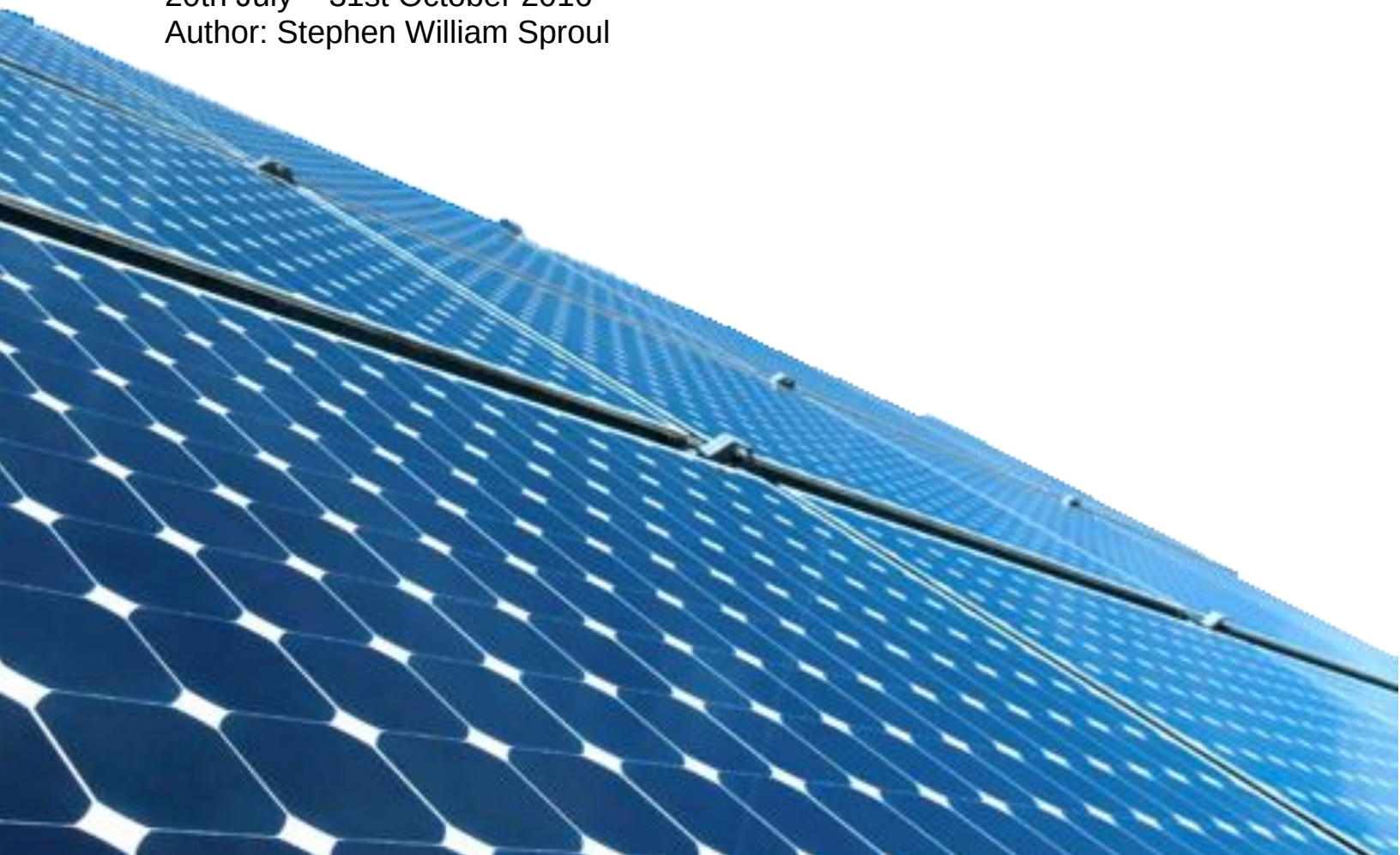

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This report provides a candid assessment of the author's experiences, drawing comparisons to the Australian electricity supply industry. Statements and material contained within this report (except where explicitly referenced) are the expressed opinion of the author and not that of any person or organisation. Any reproduction or referencing of this report should reflect this.

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Thank you to my mum and dad who have always supported and inspired me in equal measure to do my best.

The author would like to thank, last but not least: the E. S. Cornwall Memorial Scholarship and its Board for the fantastic opportunity the scholarship provides for professional and personal development of young engineers. I hope to show this gratitude through my contributions to advancing the Australian power industry now and in the future.

EXECUTIVE SUMMARY

The power industry is at a critical moment in time with respect to its future viability, enabling the transition to a low carbon energy system and providing ongoing value to customers. Distribution and transmission service operators continue to manage network investment with respect to load growth, quality of supply, reliability and safety, but with increasing levels of distributed energy resources and centralised renewable generation connecting to the network. Queensland now, along with South Australia, has the highest level of rooftop solar per capita in the world. New products, such as residential and community energy storage systems are offering customers an alternative approach for meeting much of their electricity needs. These technologies are fundamentally changing how the electricity network operates both technically and from a business perspective.

Integrating more centralised renewable generation and distributed energy resources, lowering electricity prices and maintaining similar levels of reliability, quality of supply and safety are mutually exclusive following traditional approaches. Utilities must adapt to remain relevant and competitive in this rapidly changing environment, appropriately leveraging new technology and adapting business models. This is required to ensure that the electricity network plays a useful role in the future energy system.

This report discusses and reflects on the work conducted for ABB's Microgrid and Distributed Generation Research and Development team in Genova, Italy, which focused on assisting with the challenges discussed. Specifically, these areas were:

1. Control systems to increase the level of renewable generation in isolated power networks
2. Grid applications for battery energy storage systems

During the time working in Italy there were a variety of learnings, however four key aspects applicable to the Queensland Power Industry are:

1. Battery energy storage systems are an economic solution now on typical electricity networks for high power low energy applications. (More expensive grids to operate and maintain offer opportunities for more energy intensive applications)
2. Only modest amounts of battery energy storage are required to facilitate marked increases in renewable generation on isolated networks. Opportunities for battery energy storage to provide stability and smoothing for Queensland's isolated sites should be assessed today.
3. Observable and controllable photovoltaic generation coupled with low cost controllers offer a cost effective method of increasing renewable generation and reducing fuel consumption in isolated power networks.
4. Sophisticated power system modelling can offer opportunities to reduce costly time on site.

I will continue to work for ABB, Italy until the 9th of December. During this time, I will work further on battery energy storage applications and perform technical modelling of photovoltaic plant controllers for grid integration and their utilisation for grid services. Finally, I will continue working to secure a position in North America from January to June 2017.

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GLOSSARY

Acronym / Abbreviation	Definition
AC	Alternating Current
ARENA	Australian Renewable Energy Agency
AVR	Automatic Voltage Regulator
BESS	Battery Energy Storage System
C rate	Battery discharge rate (Discharging or charging power/Energy capacity)
CSC	Current Source Converter
CSO	Community Service Obligation
DER	Distributed Energy Resource
DSO	Distribution Service Operator
EHV	Extra High Voltage
EU	European Union
EV	Electric Vehicle
f	Electrical Frequency - cycles per second (Hz)
GESS	Grid Energy Storage System
GIS	Gas Insulated Switchgear
GPO	General Purpose Outlet
GW	Gigawatt
HV	High Voltage
HVDC	High Voltage Direct Current
I	Current - Coulombs per second (Amperes)
I/O	Input / Output
IEEE	Institute Electrical Electronic Engineers
IGBT	Insulated Gate Bi-polar Transistor
IPD	Interface Protection Device
kVA	Kilovolt ampere
kW	Kilowatt
kWh	Kilowatt hour
LV	Low Voltage
MPPT	Maximum Power Point Tracker
MV	Medium Voltage
MVA	Megavolt Ampere
MW	Megawatt
OLTC	On load Tap Changer
P	Real Power (W)
p.u.	Per Unit
PCC	Point of Common Coupling
PV	Photovoltaic
PVD	Photovoltaic Diesel
PVPC	Photovoltaic Plant Controller
PWM	Pulse Width Modulation
Q	Reactive Power (VAr)
S	Apparent Power (VA)
STATCOM	Static Synchronous Compensator
TSO	Transmission Service Operator
UHV	Ultra High Voltage
UK	United Kingdom
V	Voltage - Joules/Coulomb (V)
VAr	Volt Ampere Reactive
VSC	Voltage Source Converter

1 INTRODUCTION

This report in the first of my E.S. Cornwall scholarship quarterly reports.

1.1 MOTIVATION

Distribution and transmission service operators (DSOs and TSOs) have always had to balance network investment against quality of supply, reliability and risk. Managing these priorities continue to be at the core of their business but in addition, various drivers are pushing increasing levels of renewable generation onto the network and new technologies such as battery energy storage are offering customers an alternative for meeting much of their electricity needs. These technologies are fundamentally changing how the electricity network operates. DSOs and TSOs must to adapt to remain relevant and competitive in this rapidly changing environment, appropriately leveraging new technology and adapting business models to secure a useful role in the future energy system.

The increase in residential solar in Queensland in the past five years has been dramatic, transforming the distribution network. Queensland now, along with South Australia, has the highest level of rooftop solar per capita in the world. [1] Large-scale renewable energy projects in Queensland had been limited in the past, but are now rapidly progressing, particularly due to Federal Government funding arrangements such as the Australian Renewable Energy Agency (ARENA). [2] Battery energy storage is also becoming cheaper and is expected to follow a similar cost curve to solar PV. [3] A range of home battery energy storage products are now available on the market, which when coupled with rooftop solar, will become an affordable alternative to the grid for customers to source most their energy.

The electricity network hasn't faced such challenges in almost a century and needs to evolve to continue to provide value to customers. As well as economics, there is also continued political drivers with the Queensland Government's 1 million solar rooftops policy and 50% renewables by 2030 targets. [4] At the same time, there is pressure to lower electricity prices for consumers whilst maintaining similar levels of reliability and quality of supply are expected. Following traditional methods, achieving all of these are mutually exclusive.

In addition, Regional Queensland has significant challenges to supply remote areas, including islands in the Torres Strait, in a cost effective manner. The community service obligation (CSO) is a government payment to subsidise the cost of these areas. This payment was $596 and $498 million for 2014-15, 2015-16 respectively. [5, 6] This is a major burden on the Queensland budget and reducing this is important in reducing state debt. These sites are currently supplied by diesel generation and renewable penetration has been limited to date because of the stability problems intermittent generation can introduce. Leveraging new technology is the only way to enable more renewables, remain relevant to customers, improve affordability and reduce exposure to increasing diesel fuel prices.

These challenges are faced by utilities the world over but are shaped by different political environments, climates, network topologies, customer densities, appetites for risk and financial capabilities. These conditions provide different perspectives and drive different approaches in innovation. Learning from these different approaches, especially in such a fast-paced environment, will be a great asset for helping Australia rise to the challenges discussed.

1.2 AREA OF RESEARCH

My area of research for the E.S. Cornwall Memorial Scholarship aims to assist the Queensland and Australian power industry meet the challenges outlined and is described by my research theme:

Improving utilisation, renewable hosting and affordability through new technology

Within this theme are some key aspects I have aimed to be involved with for the purposes of advancing the Queensland and Australian electricity industry. These are:

- Investigate smart grid infrastructure to learn how to make a variety of technologies work together in an effective and collaborative way. This can help make the most of Australia's climate rather than view renewables as disruptive to the network.

- Understand active network management and control strategies to allow greater penetration of renewables and improve network utilisation. This as oppose to traditional passive approaches that are limiting and require redundancy and operating margins which come at a cost.

- Learn from leading energy storage integrators and power electronics manufacturers to better understand integration complexities as well as operation and control methodologies. This will extract the full value from these devices to operate effectively on Queensland networks.

- Utilise every opportunity to attend and present at conferences, workshops and undertake site visits to maximise opportunities that can be more restricted whilst based in Australia.

Based on these objectives I secured employments with ABB's microgrid and distributed generation research and development team in Genova, Italy. ABB are a world leading organisation and working within this team would give me the opportunity to work with integrating renewables and distributed generation in both on grid and off grid scenarios. This covers a large part of my theme.

Lastly, the author recognises the irony of researching microgrids on the E.S. Cornwall Scholarship. E.S. Cornwall was instrumental in creating the interconnected Queensland electricity network of today and part of my research topic is to disconnect the system into segments. However, both interconnection and microgrids aim at improving the electricity network, with the goals of improving cost, reliability and operation. The power industry is at a time where the landscape is changing and it needs to evolve, much like when the system was first interconnected approximately 80 years ago.

1.3 THE SEARCH

It would be remiss of me not to mention my search for employment, because I gained a great deal from the process. During my search, I learnt a lot about European utilities, manufacturers and projects. There is a significant amount of work occurring that is aligned to my topic and many resources and case studies to benefit from. Therefore, I feel it is appropriate to discuss a few.

In addition, it was very challenging to secure work in Europe. Many companies are undergoing re-structures and cost cutting measures, all of which are understandable at this point in time. Whilst understandable, many difficulties seemed analogous of the situation faced with managing new technology and the changing energy landscape. I think it is important, whilst challenging, to base each case on its merits rather than always following the same approach, seize opportunities for what they are, even if they aren't typical and introduce some more flexibility into large and rigid companies, systems and processes. Finally, I have benefited from a lot of people's good will and passion to advance the power system in my search which seems to be an attribute of the power industry the world over and will be important to harness in the challenges to come.

1.3.1 Enel Group

Enel are a leading multinational energy company with subsidiaries including Enel Distribuzione, (now e-distribuzione) a DSO and Enel Green Power, a renewable generation business. Enel operates in over 30 countries on four continents with a net installed capacity of over 89 GW and services 61 million customers. [7] Enel operates hydroelectric, thermoelectric, nuclear, geothermal, wind, solar and other renewable sources with a generation mix shown in Figure 1.

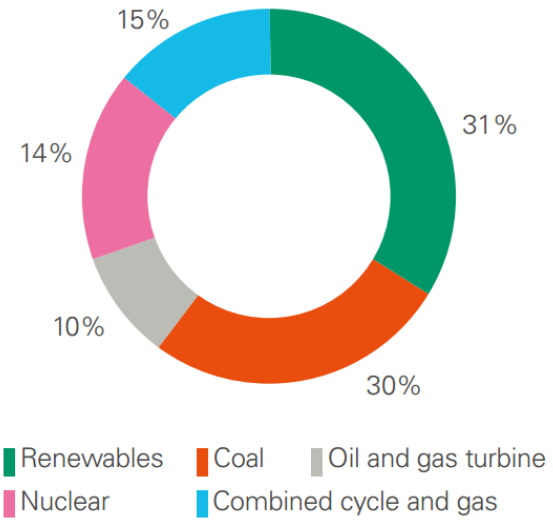


Figure 1. Enel Group net electricity generation by source 2015. [8]

1.3.1.1 Enel in Italy

Enel is Italy's largest power company. [7] It operates 31 GW of power generation of which about 40% is renewable including hydroelectric. 10% of the total renewable generation is operated by Enel Green Power. [8] In addition, Enel manages most of the electricity distribution network in the country through e-distribuzione and offers integrated products and service solutions for electricity and gas to its 31 million Italian customers. Figure 2 shows an overview of Enel in Italy.

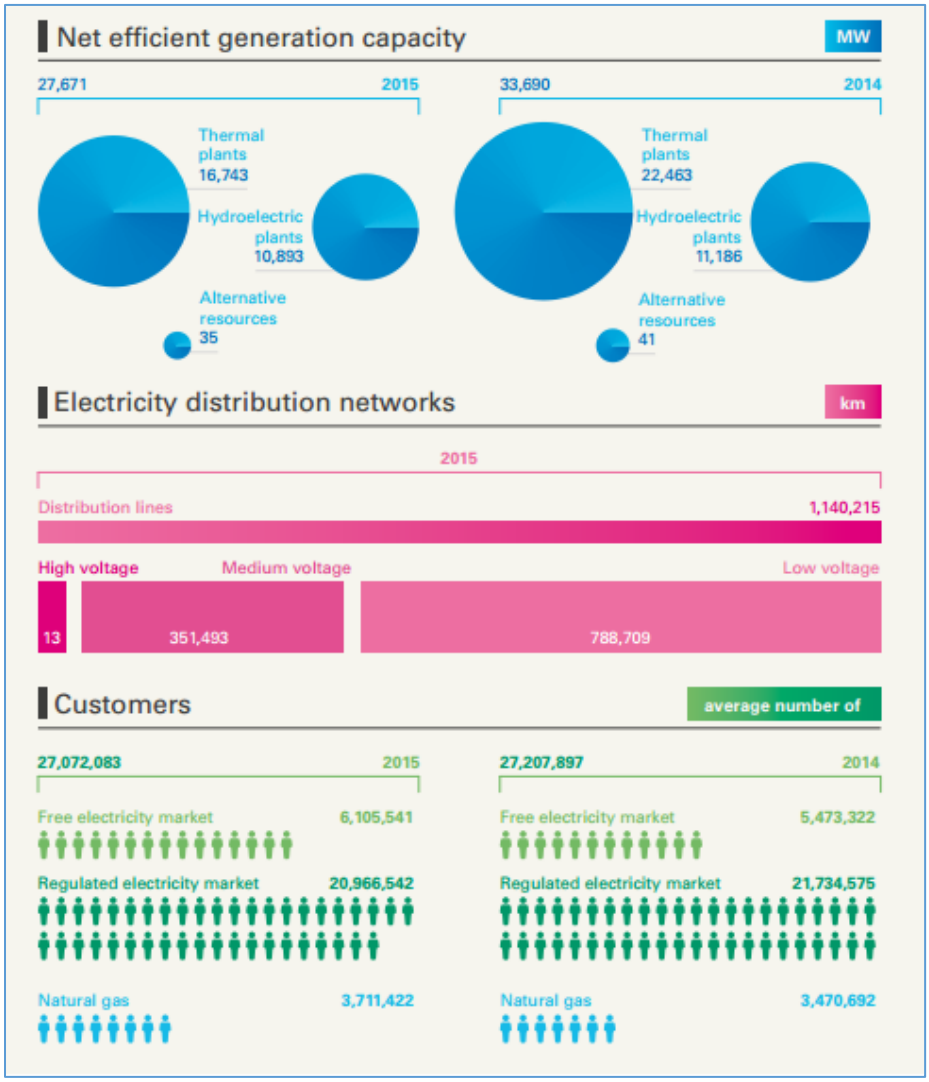


Figure 2. Overview of Enel in Italy. [8]

There were several reasons I targeted Enel in Italy. Firstly, they operate in an area with a climate most similar to Queensland with respect to Europe and have experience with connecting and integrating large scale solar plants. This experience is both on the developer side, through Enel Green Power and the DSO with e-distribuzione which provides a complete overview. e-distribuzione also provide services around solar and home energy storage systems, two technologies that are extremely relevant to Queensland.

I was also interested in working with e-distribuzione because they are responsible for operating unique electricity tariffs that have been established to be cost reflective of network investment. The only other geographical area in my experience that operates similar tariffs is California. [9] Cost reflective electricity tariffs are fundamental for Queensland to achieve a fair electricity price for all customers. Without a market mechanism to provide feedback to the customer linked to network expenditure, affordability will be impossible to achieve, and contribute to the so called 'death spiral'. With regard to affordability, e-distribuzione operate other interesting mechanisms

such as supply limits and scheduling of power usage that again, in my experience is unique to Italy and discussed in Section 4.1.2. All of these factors assist with managing the cost of electricity.

Finally, Enel are a very active participant in various research projects that align with my theme, two of which are discussed in the following sections. I have made some contacts at Enel and discussed their work under the Grid4EU project and hope to continue to share learnings where possible.

1.3.2 EvolvDSO

The project EvolvDSO considers the growing relevance of distributed energy resources (DER) in the generation mix as well as the increase in pro-active demand for electricity. Due to this power systems and their mode of operation need to evolve. [10] EvolvDSO is funded by the EU and involves a number of industry and academic partners across Europe. The project aims to define future roles of DSOs and develop tools to assist in progressing to these new roles. This is based on various scenarios driven by different DER penetration levels, varying degrees of technological progress and differing customer acceptance patterns. The project reports are publicly available on their website at [10].

1.3.3 Grid4EU

The Grid4EU project was another project, co-funded by the EU and involved six of the largest and most influential utilities in Europe. [11] Each utility and their partners looked at a different aspect of smart grids to assist in the successful deployment within Europe in the future. The six projects, and the key focus, can be seen in Figure 3.

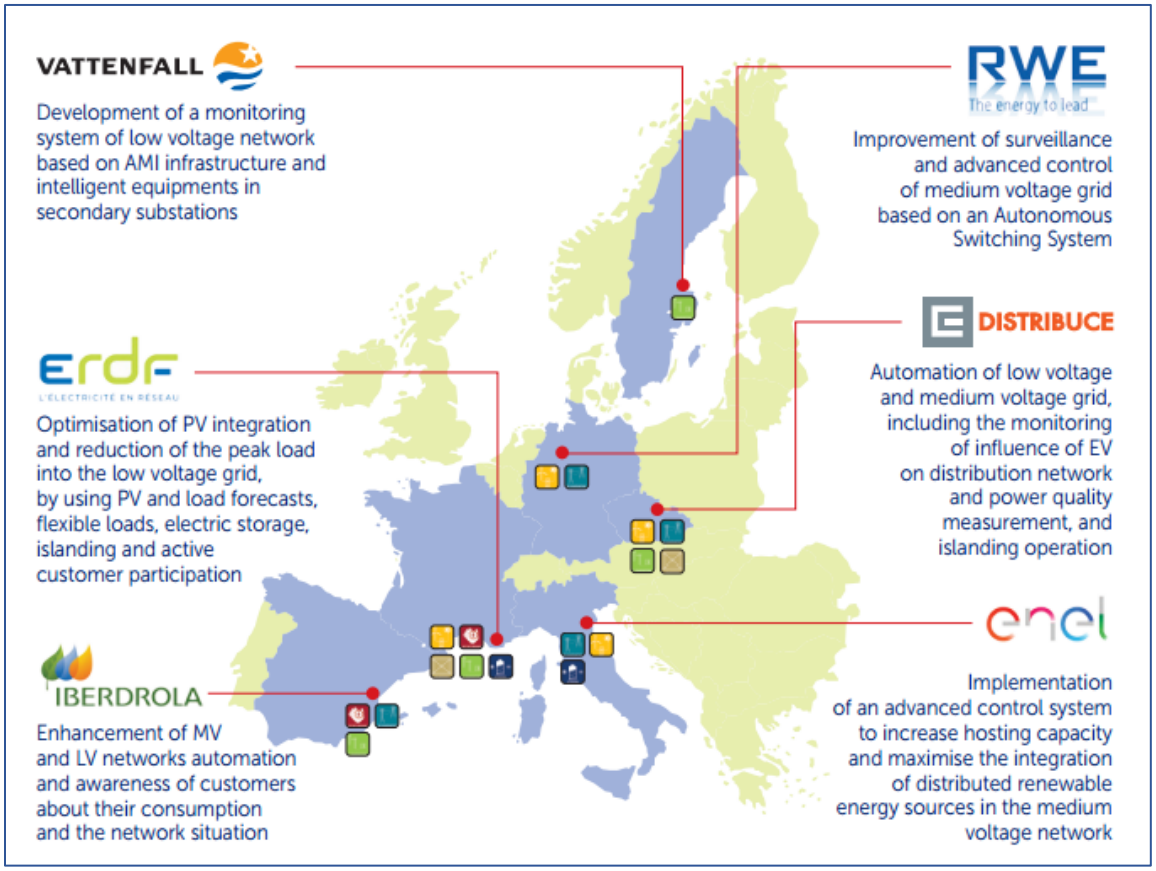


Figure 3. Grid4EU Project Overview. [11]

I focused primarily on ERDF and Enel projects as they had the most relevance to my theme. I since learnt more about the Enel project at the CIGRE Paris sessions. The project aimed at testing innovative concepts and technologies in real-world demonstration environments, in order to highlight challenges and remove barriers to the deployment of Smart Grids in Europe. The final report is available here [11].

1.3.4 Project Increase

Project Increase was a project I found in my search for employment. This project is co-ordinated through the University of Genk in Belgium with the aim of developing innovative three-phase grid-connected inverters and new operational and control strategies to increase the renewable hosting capacity of networks, and maintaining a reliability and quality of supply. [12]

The five scientific and eight industrial partners have all participated to research methods and design converters to focus on managing renewable energy sources in low and medium voltage networks. Voltage control, the provision of reserve and other auxiliary services that can be leveraged would be considered in addition to accessing market design and regulatory framework. [12] Finally, the costs and benefits will be assessed. These converters are being trailed on several networks throughout Europe in the second half of 2016.

Dr Bart Meersman was very generous in his advice and support but ultimately as a University based placement there were financial limitations. I am hopeful that I can visit and understand more about the work they are doing and I will meet with project representatives at European Utility Week 2016. This project has already provided value to the Queensland Electricity industry, by aiding in the understanding of inverter interactions and instability when regulating voltage with dynamic reactive compensators. More details of this project can be found at the project website here [12].

1.3.5 Vattenfall

Vattenfall is a Swedish, state owned, vertically integrated electricity, heat and gas company. It is one of Europe's largest generators of electricity. [13] They are committed to be climate neutral by 2050 and its main markets are Denmark, Finland, Germany, the Netherlands, Sweden and the UK. Vattenfall has one of the largest research and development centres in Europe which is where I was hoping to work. [14] Their work focuses on the use of smart meters and utilisation for supervision, power quality analysis and grid planning. Sweden has had a 100% penetration of smart meters for some time and Vattenfall is at the forefront in finding new ways of utilising this data. [14]

I believe smart meters are important for Queensland as DER becomes more prevalent on LV networks. Visibility of network parameters at the LV level is poor yet this is where DER is connected and where constraints are now arising. Utilising smart meters to better operate and plan LV networks and in addition, using the data for a variety of other purposes is important to extract the full value, similar to the concept of 'value stacking' for energy storage discussed in Section 3.3. Meters, being at every customer premise, are very visible to customers and need to be managed sensitively as any increase in costs can be assumed to be attributed to smart meters. This should not rule out their use, but they need to be managed appropriately. Vattenfall operate a demonstration site for Project UPGRID which focuses on improving the utilisation of smart meter data. The site is in rural Sweden close to the town of Åmål and focuses on monitoring and controlling the LV network and using smart meter data. [15] Finally, Vattenfall engineers developed the seat belt as part of managing internal workplace health and safety practises. [16]

1.3.6 UK Power Networks

UK Power Networks were very generous in their time and I would particularly like to thank Sotiris Georgiopoulos for his correspondence and efforts on my behalf. UKPN have been great supporters of the E.S. Cornwall scholarship with several previous scholars working there in a variety of important projects. Two projects in particular, managed by UKPN that interest me regarding my topic are the Smarter Network Storage Project, which Matthew Zillmann discussed in his report [17] and using active network management to control DER, EVs and large scale renewable connections in a flexible manner which is very valuable for cost effective integration. [18]

It was a difficult decision but in the end I secured employment with ABB which I will discuss in the following section.

2 BACKGROUND

2.1 ABB

ABB is a multinational corporation headquartered in Zurich, Switzerland. The company has been involved in a diverse range of areas but currently focuses on power and automation technology products and applications. ABB today is the product of many acquisitions and mergers, such as PowerCorp in 2011 and Vectek in 2008, as some examples from Australia and New Zealand. [19] Primarily however, the coming together of ASEA of Sweden and Switzerland's BBC, formerly known as Brown Boveri, two of the proudest and best-known names in European electrical engineering history, formed ABB in 1988. [20]

ABB today has approximately 135,000 employees across almost 100 countries. In December 2015 ABB's revenue was $US35.5 billion, and ranks amongst the world's largest conglomerates. [21, 22]

ABB has made significant contributions to the field of electrical and power engineering. In my first week at ABB the solar impulse flight completed its circumnavigation of the globe, the first without any fossil fuel, marking a milestone for solar energy, innovation and the company, who were a technology partner. [23] Some other key achievements are set out in Figure 4.

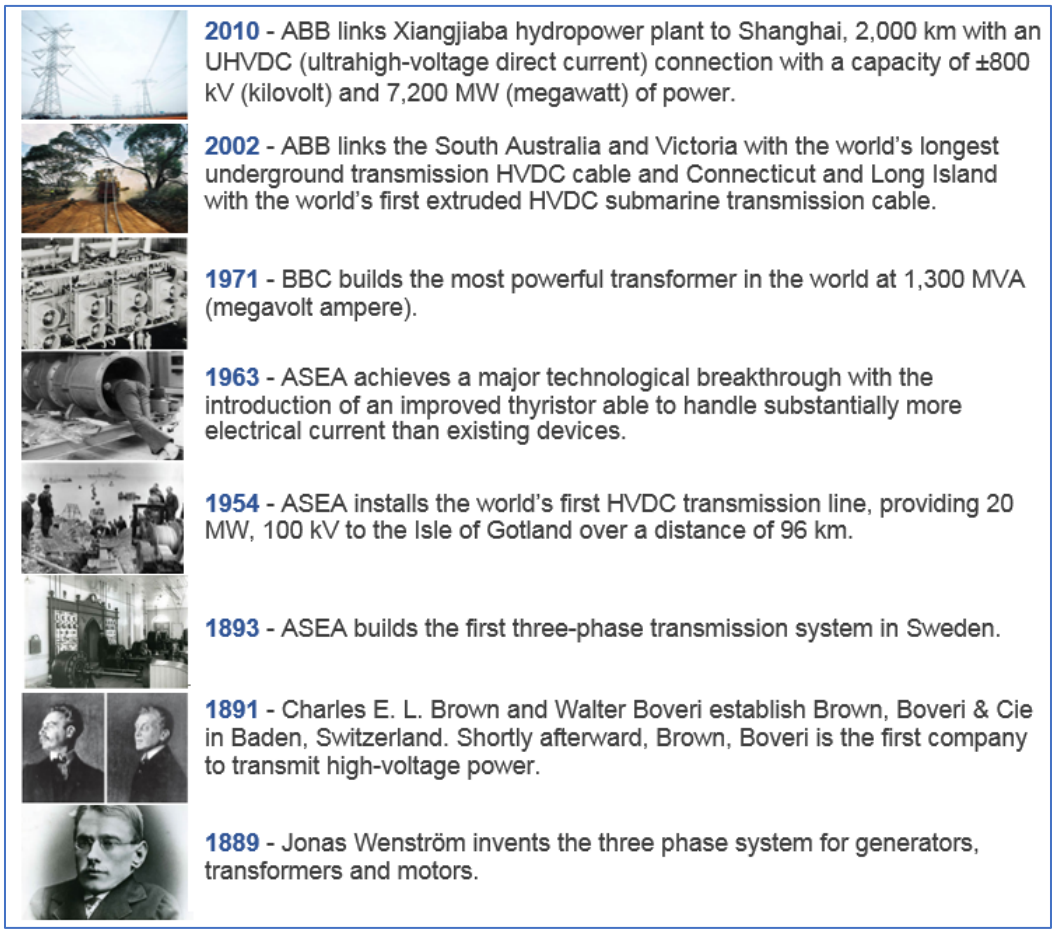


Figure 4. Time line and summary of ABB contributions to electrical and power engineering. [20]

2.2 KEY ABB PROJECTS IN AUSTRALIA

In the microgrid, renewable integration and energy storage context, many of ABB's reference sites are located within Australia. Australia, with its solar and wind resource and challenges against distance and remoteness, has the most to gain through leveraging such technology. I also believe that each of the three projects mentioned below meet a different and important application for improving the electrical supply within Australia. They each demonstrate how to overcome the technical challenges of integrating high levels of renewable generation and leverage new technology for a greater benefit. The next step however will be applying the lessons from these sites, of which external funding was received in most cases, and making these economical solutions.

2.2.1 Marble Bar

Marble Bar was one of the world`s first high penetration, solar photovoltaic diesel power stations [24]. Marble Bar is in the north of Western Australia and has 124 premises. [25] The existing generators supplying the town were at the end of their economic life in 2006 and were being supplemented by mobile generation units to ensure a continued reliable electricity supply. The replacement solar and diesel system comprises of the following:

- Diesel Generation - 4 x 320kW Diesel Generator
- Photovoltaic - 300kW of single axis tracking photovoltaic arrays
- ABB PowerStore™ Flywheel - 1 x 500kW/18 MW.s flywheel
- Microgrid Plus Control – Control system for power station

An aerial photo of Marble Bar can be seen in Figure 5.

Figure 5. Aerial photo of Marble Bar Power Station.

The system allows 65% of daytime load to be met with sunshine and has reduced diesel consumption by 405,000 litres annually, (35-40%) saving 1,100 tonnes CO_2. [26] Contrary to

industry concerns about instability introduced by renewables, supply to the community has remained has remained stable and in fact slightly improved in reliability. [25]

This is a valuable project to demonstrate how to overcome the technical barriers to high penetration renewable integration on isolated networks. The decision at the time to select a solar/diesel option over was marginally more cost effective than a solely diesel option when comparing full life cycle costs. [25] Horizon Power received partial funding for this project, $4.9 M from the Commonwealth's Renewable Remote Power Generation Program, the predecessor to ARENA. The final project was completed for a total cost of $18.9 M, [25] which is a significant cost per premise served. The vast majority of these costs were associated with the civil works in an extremely rugged and remote site. It is also important to note that this was a bespoke solution that was initiated 10 years ago, and as such, an equivalent solution can be developed much cheaper today. It did prove the technical concepts and now providing a similar solution for a lower capital cost, which is discussed in Section 3.1.2, is key for application at other sites. Mobilisation costs are significant for similarly remote sites and managing this aspect and minimising time onsite is important to gain an economic benefit. The ongoing costs, with reduced fuel consumption are favourable, but the capital cost must be reduced to make the overall cost favourable.

2.2.2 AustNet battery storage trial

AusNet Services chose to trial a grid-connected energy storage system (GESS) to explore the ability to manage peak demand with the potential to defer investment in network upgrades. [27] This project demonstrated utilising energy storage in an urban setting. ABB Australia led the project with a suite of their products and integration of Samsung SDI batteries. The energy storage system was a 1 MW/1 MWh PowerStore™ Battery which can be utilised as a standalone system or as part of a microgrid, seen in Figure 6. [27]

Figure 6. ABB's PowerStore™ Battery energy storage system which can be deployed stand alone or as part of a microgrid.

The microgrid also included a diesel generator, connection to the grid and appropriate protection. [27] Whilst the system focused on peak demand management for network investment deferral, improving power quality and system islanding were also objectives, with the later aiming to provide an effective method of managing continued supply during temporary feeder

disconnections for line maintenance or bushfire prevention [27]. The system is fully portable and redeployable, installed on an industrial lot in several transportable shipping containers and transportable skids, which is an important aspect of energy storage and is discussed in Section 3.3. The GESS, an Australian first of this type and size in an urban microgrid setting, seen in Figure 7, was commissioned in December 2014. [27]

Figure 7. AustNet battery storage trial photo. [27]

2.2.3 DeGrussa Copper-Gold Mine

Mining is Australia's and Queensland's largest industry. The DeGrussa Copper-Gold Mine in Western Australia is a significant project for the mining sector and an example for integrating high penetrations of renewables for use in the supply of mines. This site was previously supplied solely by diesel but through a range of funding streams, the Clean Energy Finance Corporation $15 million, ARENA $20.9 million and Neoen contributing most of the balance, the following system was installed for a total cost of $40 million. [28] The complete system consisted of:

- 10.6 MW of single axis tracking solar PV
- 5 x 2 MW inverters with solar MV stations and transformer
- PowerStore™- Battery grid stabilisation 2 MW/1.8 MWh
- Microgrid Plus control system
- Integration with existing 19 MW diesel power station

ABB were the technical lead on this project, which was commissioned in 2016. This hybrid system is currently the largest integrated off-grid solar, battery storage and diesel plant in Australia. [28] The expected diesel fuel saving is 5 million liters per year, cutting diesel consumption by 20% and reducing CO_2 emissions by 12,000 tonnes per year. Whilst mining operations are private and the use of such a system is the prerogative of the mine itself, it highlights what is possible and provides a reference site for managing the technical aspects of high penetrations of renewables. For Queensland, it demonstrates an alternative to grid connection when considering the most cost effective way to supply a mine. In addition, it assists the microgrid market in Australia, where the benefits of mines adopting such approaches can develop technology and expertise for assisting other off grid sites around Queensland.

Figure 8. DeGrussa Copper-Gold Mine in Western Australia site photo. [28]

2.2.4 Summary of Australian ABB Projects

All of these projects share a similar control system, the Microgrid Plus System, which has been implemented in different ways. This control system has played a large part in my experience with ABB. They all have a different application but equally a strategic benefit for Australia. These being;

- Increasing renewables and reducing diesel fuel consumption in off-grid networks;
- leveraging microgrids and energy storage for network deferral and other factors in grid-connected settings; and
- Improving the supply of Queensland and Australia's largest industry, mining, in a more environmentally friendly way.

2.3 ABB CORPORATE RESEARCH CENTRES

ABB have their own corporate research centres that are not directly linked to the product and system businesses allowing for their independence from day to day project work and to generate new ideas and advance existing technologies in a strategic way. The research and development is focused on eight key research areas [29].

Switching - Devise cutting-edge AC and DC interruption technologies for the entire voltage range.
Materials - Investigate materials for future products as well as improved manufacturing processes.
Electromagnetics - Devise novel products and systems using insights into electromagnetics, dielectrics, heat transfer, acoustics and electrochemistry
Power Electronics – Develop novel power electronics solutions and power semiconductors for diverse applications

Sensors - Create innovative measurement solutions for electrical and industrial systems and secure, smart electronics
Mechanics - Analyse, design and track manufacturing advances and maintenance of diverse mechanical systems (robotics to switchgear)
Control - Innovate automation, operation, protection and maintenance solutions for industrial and electrical systems
Software - Create sustainable, secure and user-friendly software automation solutions and communication technologies

In addition, ABB collaborate with approximately 70 universities in addition to their research centres [29].

3 PLACEMENT EXPERIENCE

On the 20th of July 2016 I began working with ABB's Microgrid and Distributed Generation Research and Development team in Genova, Italy. This team has four key focus areas, shown in Figure 9, and would offer me opportunities to extend my knowledge in controlling renewables in islanded power systems, modelling and integrating large scale renewable power plants, control methodologies for inverters and battery energy storage.

Workstream	Functional Layer	What we deliver
Design and Consultancy Tools	Tools and workflows to support Microgrid lifecycle, from system feasibility study to plant service	Optimized workflows, validated models, plug-ins on 3rd party tools, new tools
Modular Plant Solutions	Modular plant solutions for microgrid system business (internal and external)	Modular hardware platforms and solutions
Microgrid & Renewable Automation	Microgrid and Renewables Automation unit and base control functions	MG and RA control libraries, packaged solutions, HMI templates, faceplates, platform independent SCADA libraries
Advanced Software applications	Online optimization, commitment, Energy & ancillary services, Analytics & Remote Services & forecasting & Aggregation	Advanced SW applications: Optimal operation & Informatics based analysis for Diagnostics, Evaluations, and Performance analysis

Figure 9. Summary of Microgrid and Distributed Generation Research and Development team's function. [30]

Figure 10 shows where I am located within the organisation. In addition to the typical functional reporting lines there are regional reporting lines that create a matrix structure rather than solely a hierarchy structure which is relatively unique in my experience.

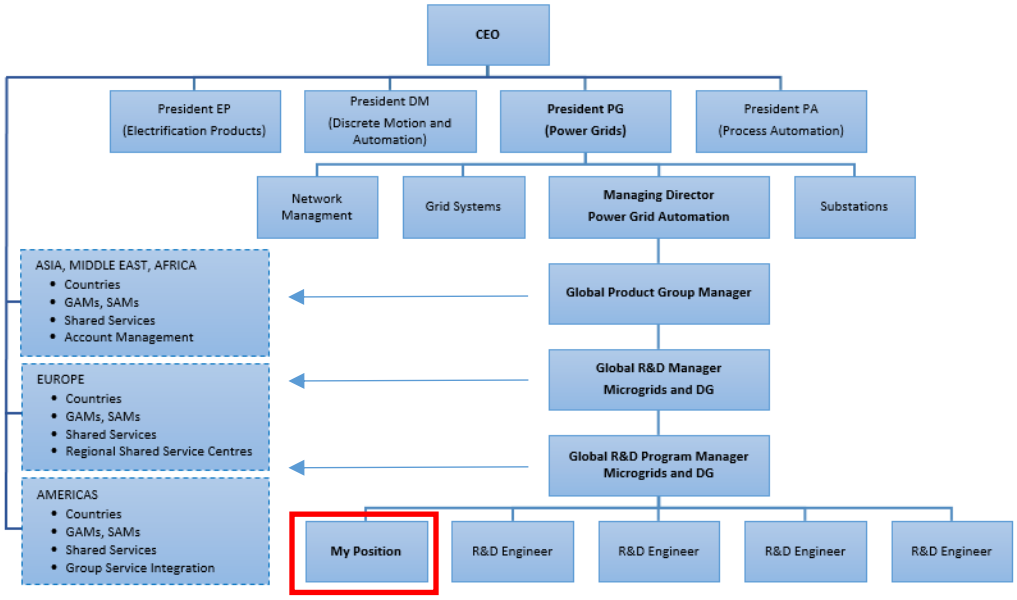


Figure 10. Where I am located in the ABB organisation. [31]

3.1 CONTROL STRATEGIES FOR MICROGRIDS

My first task involved control strategies for microgrids. The definition of a microgrid is not standardised, with the main difference, being whether it must operate as both isolated and grid connected or whether mini-grids, that always operate islanded are also considered to be microgrids. For the purposes of this report the following definition from CIGRE will be used.

"*Electricity distribution systems containing loads and distributed energy resources – operated in a controlled, co-ordinated way either connected to the main power network or islanded* [1] "

I was to understand ABB's current microgrid controller that is used solely for off grid applications and incorporate a grid connection device to allow the system to operate in both grid connected and stand-alone modes.

I initially had to research more about isolated systems as well as ABB's current product offering, Photovoltaic Diesel 2.0 (PVD 2.0).

3.1.1 Technical Background

In the context of isolated power systems, renewable integration can pose problems to the performance of the system. These problems are caused by the intermittent nature of renewable generation. This can affect the performance and stability that on larger interconnected grids can be absorbed. Isolated grids can vary in size but for the purposes of this report, systems less than 5 MVA will be considered. Solar and diesel mini-grids will be the focus in this report but the renewable energy source can be of any variety.

Diesel engines are the most common electricity generation method used in remote mini-grids. This is because they are low cost, reliable and have favourable technical characteristics for the application, such as quick start, load following capabilities and part load efficiency. [32] [32] provides a comprehensive background on diesel generators, particularly in the mini-grid context.

There are two key control systems diesel generators have which is an automatic voltage regulator (AVR) and governor. The AVR controls the system voltage whilst the governor controls the system frequency. Full details on the operation of these can be found in [32] but for the purposes of this report it need only be known that the AVR controls voltage and the governor controls the frequency.

With diesel generators being the most common generation method, successfully combining renewables into the generation mix must not compromise the operating characteristics of diesel generators. However, the intermittent output of renewable generation, in the isolated grid context has several impacts on diesel generators, when introduced beyond a level of approximately 10 – 25% peak penetration. The main operating factors that have significant influence over the integration of renewable generation within a mini-grid are:

1. Minimum load
2. Spinning Reserve
3. Step-load
4. Minimum Run time

[1] CIGRE Paris Sessions 2016

These will be discussed in turn.

Minimum load – An engine load factor is the current output of the generator divided by its rated capacity. Most engine manufacturers recommend not operating engines for prolonged periods below 40 per cent load factor to avoid violating warranty conditions. Extended operation at low loads ('underloaded') can cause a range of problems which reduce engine performance and may require premature engine maintenance or rebuilding. Generators typically operate between 50 and 90 per cent of rated capacity to avoid these issues, and to maximise thermal efficiency.

Spinning reserve – The power system must have enough generation to meet demand. The amount of spare diesel capacity that is online to meet an increase in load is defined as spinning reserve. In the context of renewable penetration, an increase in load also results from a loss of renewable generation. The spinning reserve setpoint is a control system parameter that sets the minimum value of spinning reserve that must be available, online, at any time. In practice, for mini-grids, the spinning reserve setpoint was typically determined by the known highest load in the community that could be turned on at any time but now the loss of renewable generation also needs to be considered.

Step-load – Step load is different to spinning reserve. Where spinning reserve is the amount of generation online for a load increase, step-load is the inherent ability of the online engines to increase their output, in response to a step load increase or sudden loss of renewable generation, in a very short time frame. If the generator's step-load capability is insufficient with respect to the step change in load, this can cause the engine to stall.

Minimum run time – Generators are required to operate for a minimum length of time. Operating a generator for less time that this can cause unnecessary wear on the engine, shortening their operational life. This means that it is not possible to switch engines on for brief periods where renewable output is reduced.

These four aspects are the main barriers to renewable penetration in mini-grids because they are aspects that are impacted by renewables and are fundamental to the reliable operation of diesel generators.

Reactive power sharing is another important factor to be considered, particularly as a transition to also operating grid connected is considered as part of this task. A solar generator at unity power factor will in effect reduce the diesel generator power factor by reducing the real power contribution of the generator. Typically, alternators can operate with poor (<0.8) power factors provided they are lagging and assuming that the generators are not fully loaded. AVRs cannot regulate voltage if the power factor is leading by more than a minimum amount as per Figure 11, which highlights the typical AVR stability regions.

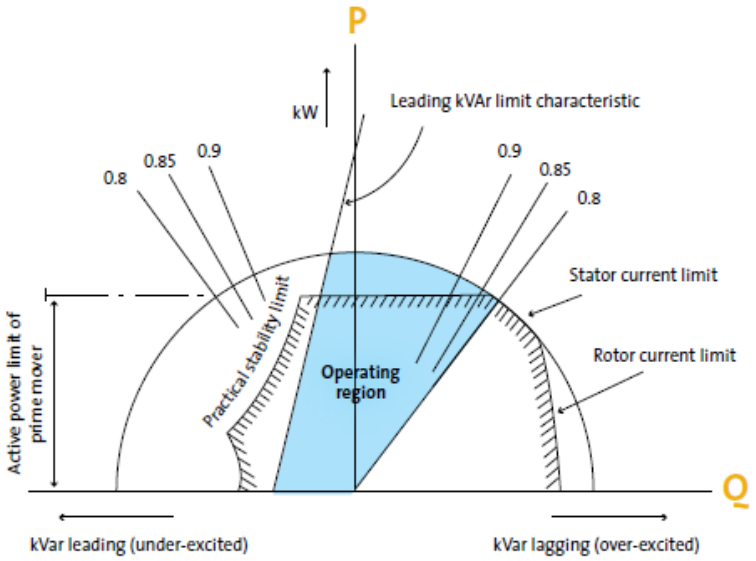


Figure 11. AVR stability curve with respect to real and reactive power output.

Ideally the solar generator and the diesel generator would share reactive power proportionally. While some modern solar inverters have this control, it is not always common. [32] It can also be common to fix the inverter power factor to a nominal value such as 0.9 lagging, which is required under Ergon Energy and Energex's new connection agreement [33] for on-grid connections, which helps manage voltage rise. However, on an isolated network, if the load power factor approaches unity, then a fixed inverter lagging power factor could force the generator power factor to lead and risk instability. The greater the solar penetration, the greater the risk that a fixed lagging inverter power factor will cause stability issues. Dynamic control of reactive power as a function of real power or voltage may also result in stability problems which need to be considered.

3.1.2 Photovoltaic Diesel 2.0

ABB currently offer, as part of their Microgrid product suite, Photovoltaic Diesel 2.0 (PVD 2.0), which is a low cost control system designed specifically for diesel and photovoltaic mini-grids, allowing for operation either as part of a grid connected configuration or in isolated networks.

Due to its simple deployment, the current generation PVD 2.0 cannot seamlessly transition between these states. The aim of this system is to be low cost and allow higher shares of PV to be connected without compromising the safe and reliable operation of the diesel generators.

Marble Bar, as discussed in Section 2.2.1 used a similar, preliminary version of this control system, focussing on high photovoltaic penetration and flywheel based grid stabilisation. However, PVD 2.0 is a productised version that aims to achieve the same outcome in a packaged kit that is swift to deployed, requires minimal engineering and importantly is very low cost. Marble Bar makes use of a flywheel to add system inertia and smoothing which allows greater renewable penetration. This is important to reach the next level of renewable penetration but also adds cost.

PVD 2.0 allows an initial increase at low cost but does require the use of energy storage, battery or flywheel. As a guide based on project experience, control alone can help increase penetration and save approximately 8 - 12% of diesel fuel [34].

The PVD 2.0 package is comprised of controllers that can be used to integrate various generation and load technologies including battery energy storage, flywheels, wind generators and load control. This allows, at such time as they become economically viable, these aspects to be added to further increase renewable penetration. Figure 12 below shows the typical layout of PVD 2.0.

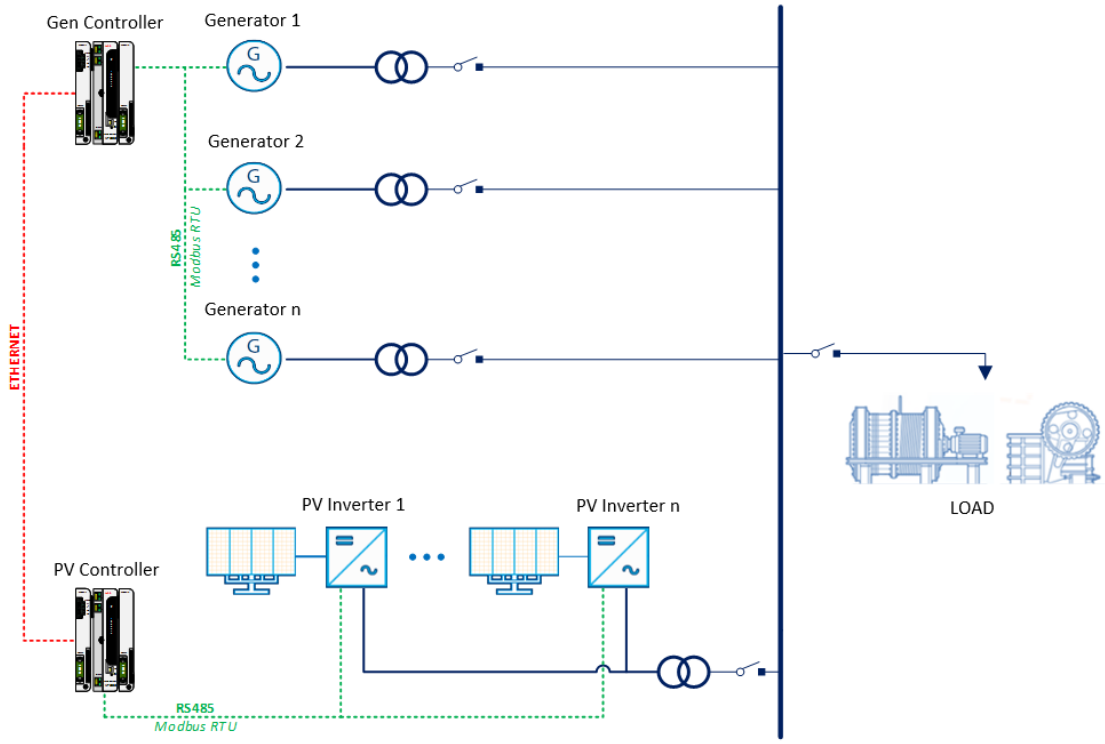


Figure 12. PVD 2.0 general layout

The PVD 2.0 system consists of a generator controller (Gen Controller) and a PV controller (PV Controller) that operate in a distributed manner, rather than a master and slave, to exchange information and act on this information every control loop. Each controller can manage many generators and inverters each (32 and 16 respectively), which will allow its use in almost any mini-grid under 5 MVA. The operating philosophy of PVD 2.0 is to monitor the generators and PV and where necessary, limit the real and reactive power of the PV inverters if it may impact the diesel generators adversely. The controller also schedules the diesel generators based on the optimal configuration at any time. There are multiple layers of this control, all with the aim of maximising renewables without compromising the operation or reliability of the system. The system also aims to operate the diesel generators as efficiently as possible when running, and where possible removing them from service to reduce fuel consumption. An important aspect of course is the PV is observable and controllable, unlike distributed rooftop solar PV.

The key features of the PVD 2.0 system are:

- Low design and engineering cost through modular and scalable controllers that are preconfigured. This helps avoid mobilisation costs and time on site in remote areas.
- Maximising fuel savings through utilising the available renewable energy, applying smart control schemes, and algorithms.

- Minimise the operating hours of diesel generators by using renewable energy firm capacity to provide spinning reserve and step load.
- High reliability through the use of redundant networked architecture.
- Low investment costs through the use of simple and non-proprietary I/O's to allow use of common off the shelve power generation control systems
- Low integration costs as existing generator control system can remain in place.
- Easy to setup and commission

To combat costs associated with staff mobilisation and specialist commissioning skills, the PVD controllers are delivered pre-configured and tested to operate with the onsite generator controller (AVR and governor) and PV inverters. The system is DIN rail mountable and packaged as per in Figure 13. On site, it need simply be mounted and wired.

Figure 13. PVD kit with Gen Controller and PV Controller pre-packaged and configured requiring on connection to plant on site.

The Gen Controller interfaces to the existing generator controller. This allows the AVR and governor to still perform the low-level functions of managing voltage and frequency respectively, but the Gen Controller sits above these to manage the generators with respect to the microgrid. The Gen Controller monitors the total generation of the Microgrid (fossil fuel and renewable), in order to understand the total load of the system.

The controller applies the minimum loading values and renewable coverage factors to calculate in real time the spinning reserve and step load requirements. The renewable coverage factors are defined during commissioning and essentially determine the maximum possible reduction in output that should be anticipated. Based on the spinning reserve and step load calculation, the controller determines a minimum operating point for the diesel generators considering as well the historical patterns of the PV generation. This value is then used to consider which generators should be online and are compared to those physically online. A decision is then taken to change the generator configuration if necessary and the generator(s) that are required are then automatically started and synchronised to the network. Once the new generator(s) are on online

and the power system is stable, the generator(s) that are not required in the configuration are automatically turned off in order of priority and with respect to their minimum run time limitations.

Whilst it is not possible to describe intimately the control system due to confidentiality purposes, there are several control layers to apply ramping, delays and other factors to appropriately manage the system against renewable intermittency.

The PV Controller interfaces to a PV generator, either a plant controller or directly to one or multiple inverters, to provide monitoring and control of the PV. A plant controller is simply a controller that aggregates the individual string inverters to ensure their operation is combine and co-ordinated effectively. The PV Controller itself, in the absence of a plant controller, can be considered a plant controller as it connects to string inverters to operate them in a co-ordinated way. This scheme provides manufacturer independent control and monitoring to allow different inverters or plant controllers from various manufacturers to be integrated into the power system. The PV Controller monitors the power output of the fossil fuel generators through measurements obtained from the Gen Controller. Using load level information from the fossil fuel generators, the PV Controller determines if the power set-point of the solar 'farm' should be increased or decreased to maintain the optimum power balance in the network. Through this adjustment, the fossil fuel generators can be maintained at their ideal loading level and specific station reserve targets maintained, while ensuring the maximum amount of renewable energy is utilised.

A subsequent task I undertook was Photovoltaic Power Plant Controller (PVPC) testing with DIgSILENT Power Factory. The purpose of the PVPC is to co-ordinate the performance of centralised or string inverters within the PV Power Plant and provide a range of grid services. This includes curtailing the real power output, as well as providing frequency response, reactive power support, voltage support and other grid services through utilising the PV inverters. I will discuss this and the mechanisms behind this operation in my following report. It is a very important aspect for PV Power Plants connecting to the grid in enabling cost effectiveness. Utilising the inverters to help the grid is important, especially as solar farms can be located where the grid is weak.

This section provided an overview of the PVD 2.0 system where the integration of a protection device to facilitate all desirable performance described above but in addition allow for a transition between on grid and off grid operation will now be discussed.

3.1.3 Photovoltaic Diesel 2.1

ABB have one thousand day projects that have a strategic value to the company. These differ from general projects and are more relevant to the research and development team. One of these one thousand day projects is to have a 'bump-less' transition microgrid product. My task was to extend PVD 2.0 to incorporate an interface protection device (IPD) that would allow PVD to operate and transition between isolated and grid connected configurations. The application for this product would be for the end of weak grids where reliability may be poor and diesel generators are used only as backup sources. The isolated operation would ensure a constant supply yet the option to connect to the grid would help minimise diesel fuel consumption.

One of the first areas identified was that to date, applications are defined as off grid/stand alone or grid connected/grid tied, and these areas have not overlapped in the past. When operating a microgrid that can be either isolated or grid connected it must satisfy the necessary requirements in each scenario.

Two potential issues that would need further investigation were:

1) Possible anti-islanding issues. When the system is grid connected, the system must have active anti-islanding as per the local grid code. Active anti-islanding essentially pulses to cause a voltage or frequency drift. This drift, once it hits passive frequency or voltage limit will cause the system to trip off line. When connected to the grid, it is part of a much larger system and will not be able to affect the voltage or frequency and remain operating, whereas when the system is operating in isolated mode, especially with high levels of renewable generation, the active anti-islanding may interfere with the AVR and governor and cause system stability issues.
2) Reactive power will likely be a grid service that is desirable to a weak grid. Reactive power is useful to manage voltage, power factor and stability. However, when operating in an isolated configuration, the reactive power function would need to be managed differently, for the reasons highlighted in Section 3.1.1.

It was proposed to perform hardware-in-the-loop testing with ABB's TRIO inverters with respect to the anti-islanding performance in an isolated grid. However, with the addition of the reactive power management, it became clear two separate operating modes would be required. The transition would also need to be managed as part of the overall PVD 2.1 operation. This also aligns with ABB's PowerStore™ Battery system that has anti-islanding when in 'grid following mode' but when operating in 'grid reference mode', to operate in parallel or instead of synchronous generation, disables the anti-islanding as it is not required in this situation.

The two operating modes that are required were firstly, grid connected in a weak grid where grid services are highly desirable and islanded where the operation must be in such a way to optimise renewables and performance as per Section 3.1.1. This basic operating diagram can be seen in Figure 14.

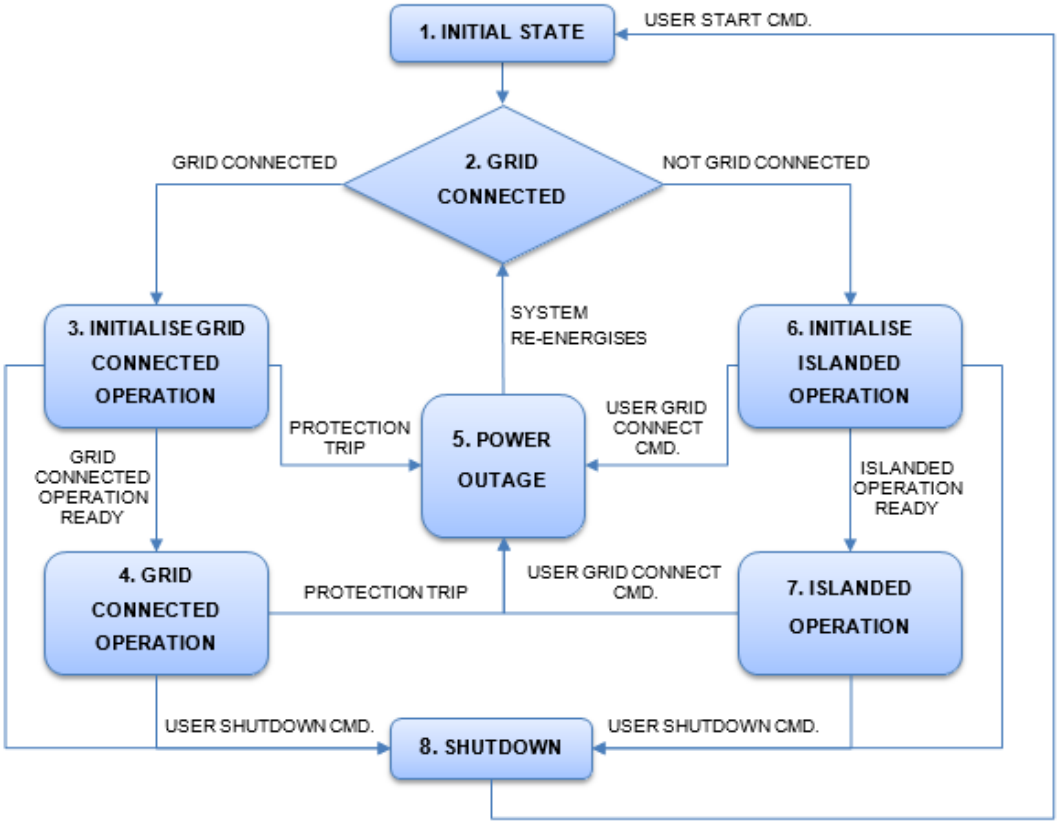


Figure 14. Flow chart of PVD 2.0 operating sequence

As seen in Figure 14, the system is defined by the status of the IPD. If this is open, the system will operate islanded in a similar manner to the existing PVD 2.0 methodology. If the grid connection is closed the system will operate similar to a PV plant controller. There are also the transitions, on-grid to off-grid and off-grid to on-grid that need to be managed to ensure each operating mode is pre-configured appropriately. The four key operating states are:

1. Grid-connected steady-state
2. Stand-alone steady state
3. Transition off grid to on grid.
4. Transition on grid to off grid.

Each of these states will now be discussed.

1. Grid-connected steady-state

The grid-connected steady-state mode is required to operate similar to a photovoltaic power plant controller (PVPC). PVPC will be discussed further in the following scholarship report as more extensive technical modelling of these systems was a subsequent task during the placement. However, PVPC are important to co-ordinate the operation of the numerous string or centralised inverters within a PV power plant. The PVD 2.1 system, when grid connected will disconnect the diesel generators and consist of only PV and loads meaning it will act much like a PV power plant. It is desirable to offer network services such as real power limiting, reactive power support, voltage support and power factor correction. This requires measurements at the point of common coupling

(PCC) or upstream to control the inverters within the system. The parameters that need to be monitored to provide these services are real and reactive power, signed (directional and leading or lagging) to limit export and offer reactive power services, frequency for frequency response and voltage for voltage support.

2. Stand-alone steady state

This state would follow the existing PVD 2.0 operating methodology, optimising renewables whilst managing them to ensure the diesel generators were not compromised. Some more details on the functions performed in this operating mode are explained in Section 3.1.2.

3. Transition off grid to on grid.

This requires firstly a signal from either an operator, if manual reconnection is requested, or a signal that the grid is present for an automatic connection. Synchronisation is then required as well as a transition in operating states such as activating anti-islanding protection and unloading and disconnecting the diesel generators. This would be done once the IPD indicates its status as closed.

Initially the IPD needs to measure frequency, phase angle and voltage for synchronisation purposes. Both active and passive synchronisation approaches were assessed and the required level of resolution and accuracy to achieve these considered. IEEE Standards C50.12 and C50.13 provide specifications for the construction of cylindrical-rotor and salient-pole synchronous generators, respectively. They specify, “Generators shall be designed to be fit for service without inspection or repair after synchronising within the limits…”

- Angle ±10 degrees.
- Voltage 0 to +5 %
- Slip ±0.067 Hz.

These were therefore used as a guide for the resolution and accuracy when measuring these parameters. Following synchronisation, the IPD would need to communicate its status as closed to remove the diesel generators from service and activate anti-islanding protection.

4. Transition on grid to off grid.

A transition from on-grid to off-grid would require energy storage to avoid an outage in an unplanned transition case. However, making energy storage mandatory would impose significant cost. The focus for PVD 2.1 is low cost and therefore by default an outage is considered to avoid the need for energy storage. Energy storage can be retrospectively added should it be desirable to avoid an outage. There is also the case of a planned transition, which would not require an outage and would be managed by synchronising the generators and then, when the real and reactive power transfer at the PCC was below and acceptable deadband, the IPD could be opened. This may be appropriate when planned maintenance on the upstream system is occurring.

An unplanned transition from on-grid to off grid would be triggered by a fault or disturbance. The IPD would need to be configurable for weak grid scenarios to provide adequate protection but not be overly sensitive, especially if an outage results. It was proposed that a similar protection curve to the CBEMA curve, seen in Figure 15, be applied. The CBEMA curve is used to define the voltage quality a device should be able to tolerate, originally for computers. A similar principal was

considered for the microgrid and that the IPD should only disconnect from the main grid should the voltage deviate from a level of power quality that can be tolerated in magnitude and time. A level of configurability in terms of magnitude and time was also important to ensure the IPD can be set up for grids of various power quality standards.

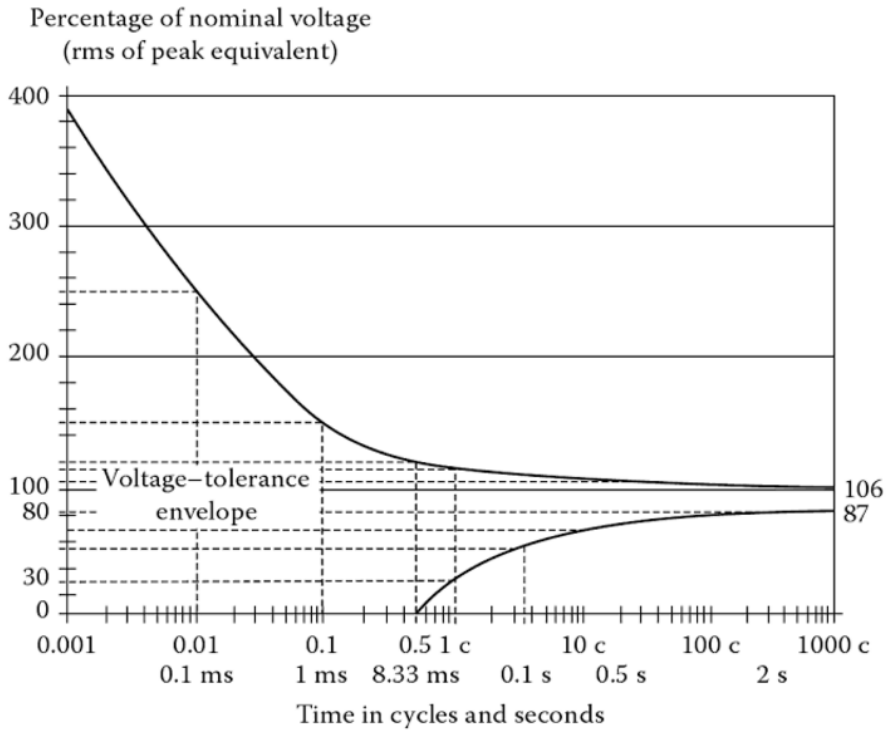


Figure 15. CBEMA Curve for power/voltage quality [35]

The IPD finally needs to communicate its open status and trigger the generators to start. The PV inverters will inhibit or disconnect depending on the local grid standards due to their anti-islanding protection.

Within the PVD 2.0 control system, the additional transitions discussed were included in the state diagram that can be seen in Figure 16.

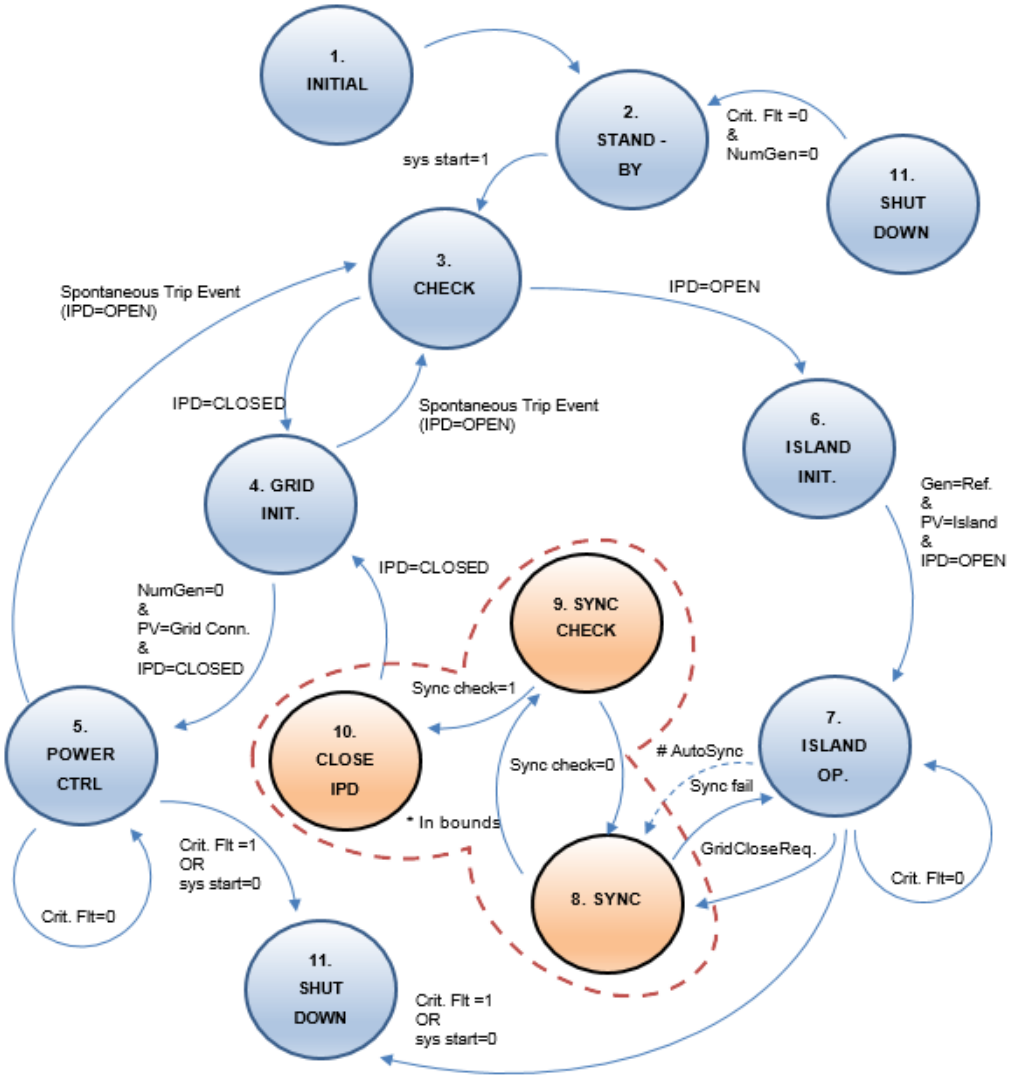


Figure 16. State machine for PVD 2.0 with added transition stage

A product specification was developed which included hardware, monitoring, signals and capabilities necessary for the PVD 2.1 system to operate in each mode and transition effectively as described. This specification was provided to external contractors where a system including suitable 3rd party meters and devices, packaged with the existing controller was compiled within the existing control cabinet. The Electrification Products, Protection and Connection (EPPC) group within ABB also had their own roadmap for developing the features of their low voltage breakers and protection systems. The Emax2 product was identified as having several features and capabilities that aligned with that required of the IPD. Several discussions were held with this group regarding adapting their product roadmap to include the required functionality for PVD 2.1 in the future.

3.2 INTERGRATING RENEWABLES SYSTEM TESTING

3.2.1 Hardware-in-the-loop testing set-up

An integral part of the research and development team is system testing. The team has developed an effective, robust and accurate testing platform to represent and test the controllers for power systems. Figure 17 shows three options for testing from fully simulating the power system and controllers in a load flow package, left, to coupling the controller hardware with a power system in a load flow package, right. Implementing the controllers in the load flow package is limiting as load flow packages are not designed for this purpose, while utilising the controller hardware can be expensive and lacks flexibility. An effective trade off that is utilised is seen in the middle of Figure 17 where the power system is modelled in a load flow package, which is a software package fit for purpose, combine with a separate simulation environment designed for controllers and system processes. Coupling these systems together gets the best performance out of each environment and provides access and flexibility for updates and refinement.

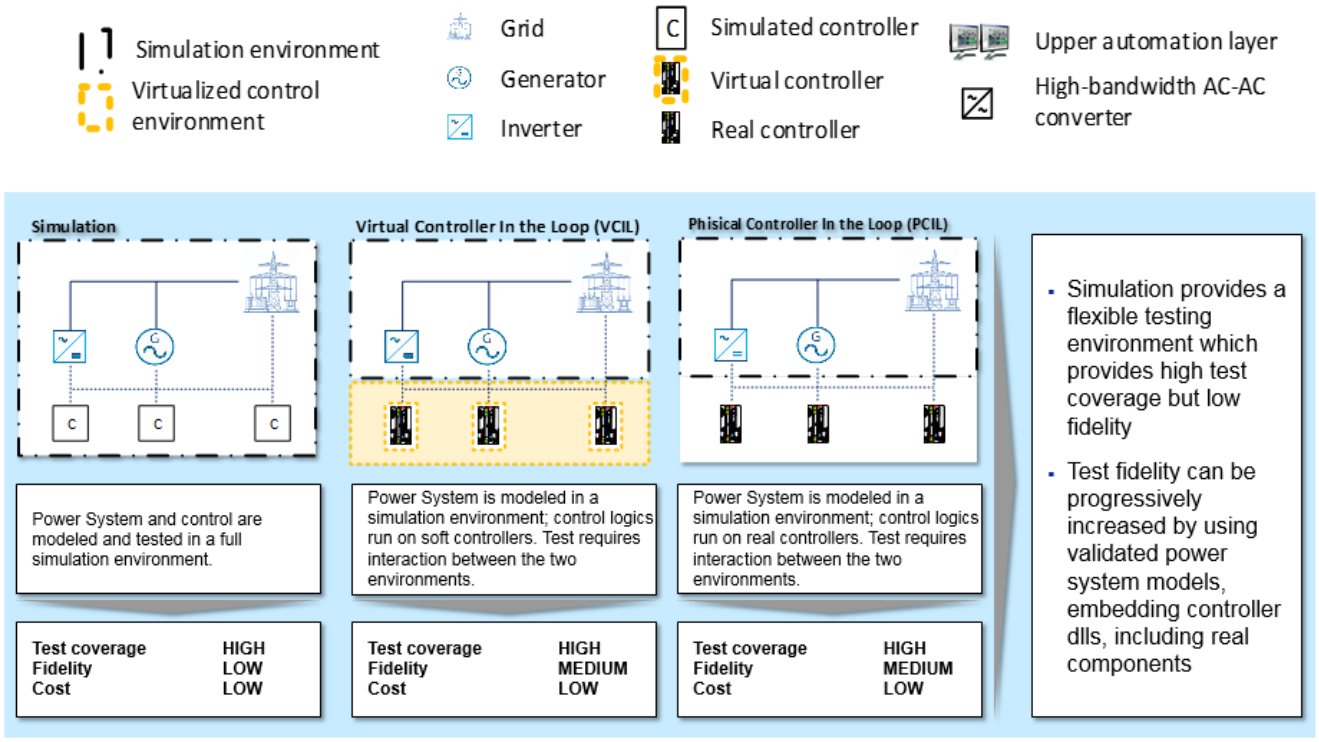


Figure 17. Comparison of testing options.

Another important aspect of this setup is it includes a standard load flow package. Utilities around the world, including those in Queensland utilise load flow packages for system analysis, which allows system models to be easily shared by utilities to test potential controller solutions. This is another area that can allow addition testing prior to arriving at site and incurring on-site related costs. The set-up, seen in Figure 18 also allows any field data such as irradiance and load data to be used for pre-configuration of controllers through testing and refining settings with site specific data.

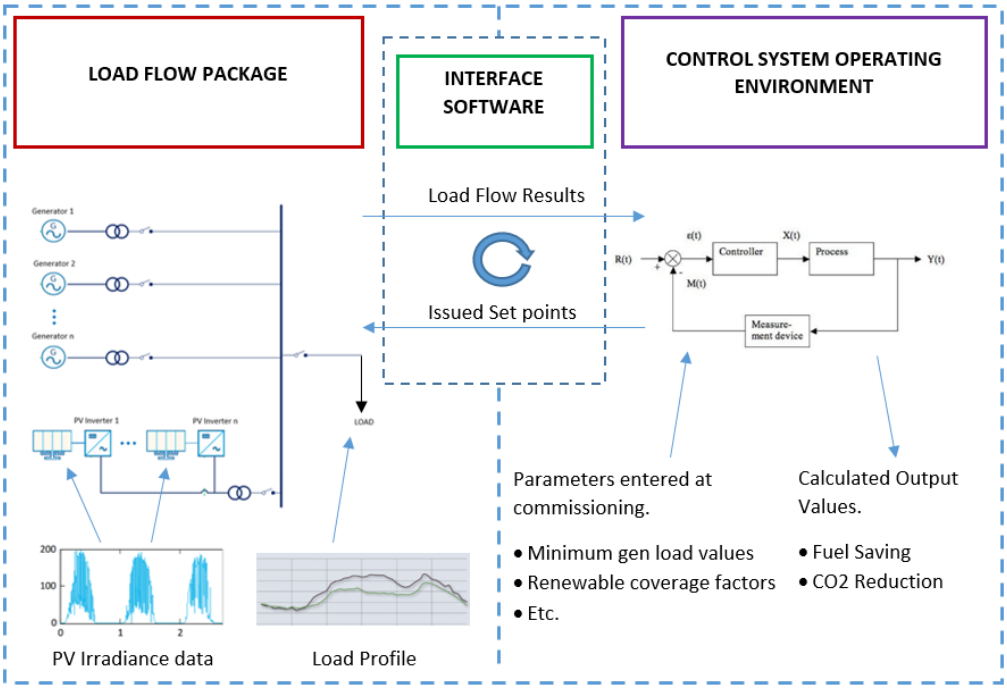


Figure 18. Testing set up with load flow package, controller test environment and interface.

As shown in Figure 18, the interface software facilitates the passing of variables between the two stand-alone environments, the load-flow package and process controller environment. This allows near real time simulation of the power system, as is commonly performed, but with settings being adjusted by the controller as appropriate based on the results of each previous load flow.

When discussing real time control it is important to consider the speed required with respect to the domain, to ensure the balance between testing complexity and accuracy required is managed. Table 1 was used as a guideline when discussing potentially enhancing this setup through collaboration with ABB's corporate research centre.

Table 1. Required 'real-time' testing speeds required for different testing domains

Testing Domain	Required Testing Speed
Communications/Control Signals	Microseconds
Power Electronics Operation	Milliseconds
Power Systems	Seconds

There are much more sophisticated real time simulators on the market that can operate much faster than the set up in Figure 18, such as OPAL RT. However, these are more complex and time consuming to set up and require reasonable resources to maintain. For the purposes of testing the controller, the test setup seen in Figure 18 is very effective and in addition, aligns with load flow packages utilised by utilities. This allows sharing of network and/or device models and provides continuity in power system testing.

3.2.2 PVD 2.0 Testing

For the PVD 2.0 system testing, it is not possible to share the results. However, some basic concepts can be shared based on the testing. Note, that these are not actual results and were produced in excel to explain concepts only.

Load profiles and irradiance profiles are loaded into the load flow package like those at the top of Figure 19. Here a peak PV penetration of less than 20% is shown. No control is used in this system other than standard generator scheduling. The blue line shows the site load, the orange the PV output and the grey line is the required diesel generator contribution.

The bottom of Figure 19 shows the generator scheduling and loading. It can be seen that, apart from a slight exceedance of 100 percent, the system operates the generators within the operating bounds of 40% minimum loading and 100% loading and scheduling the generators on and off as required.

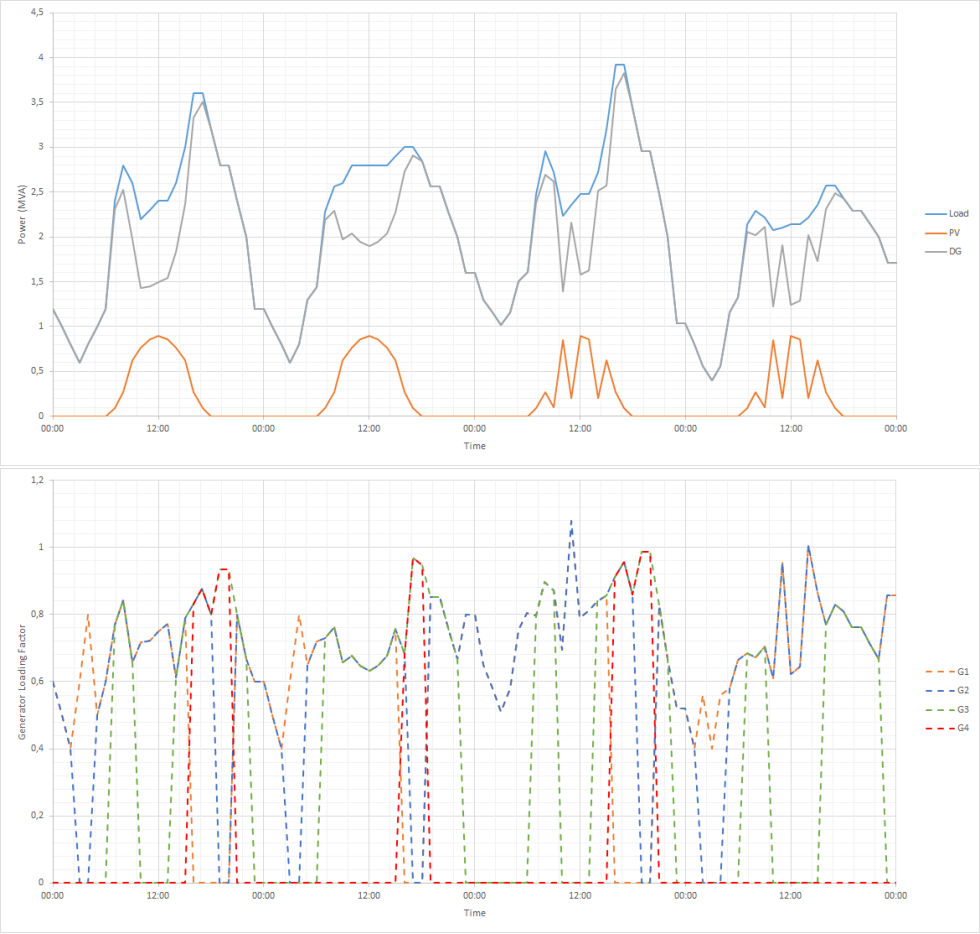


Figure 19. Example of load profile with less than 20% PV penetration top and generator contribution bottom.

Increasing the peak renewable penetration beyond 25% percent, seen in Figure 20, exposes some technical issues which will be focused in on more in Figure 21, which zooms in on the two last days which have intermittent PV output.

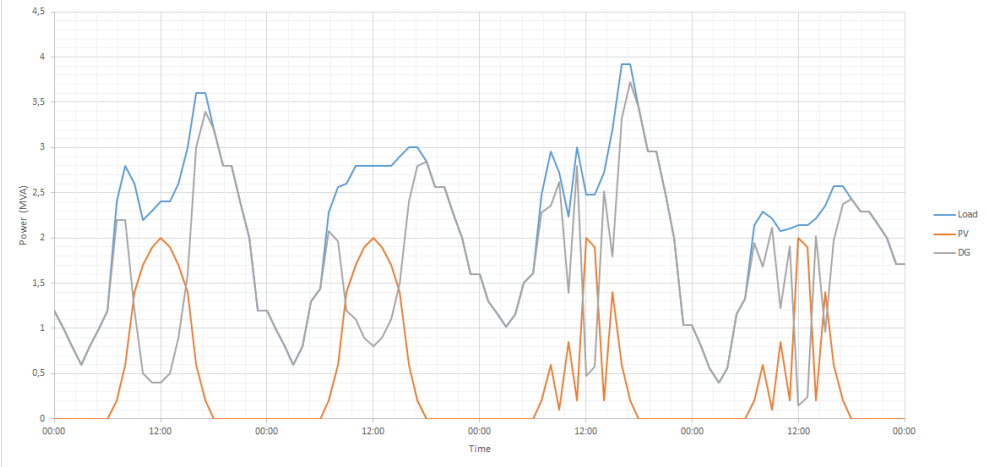


Figure 20. Example of load profile with more than 25% PV penetration.

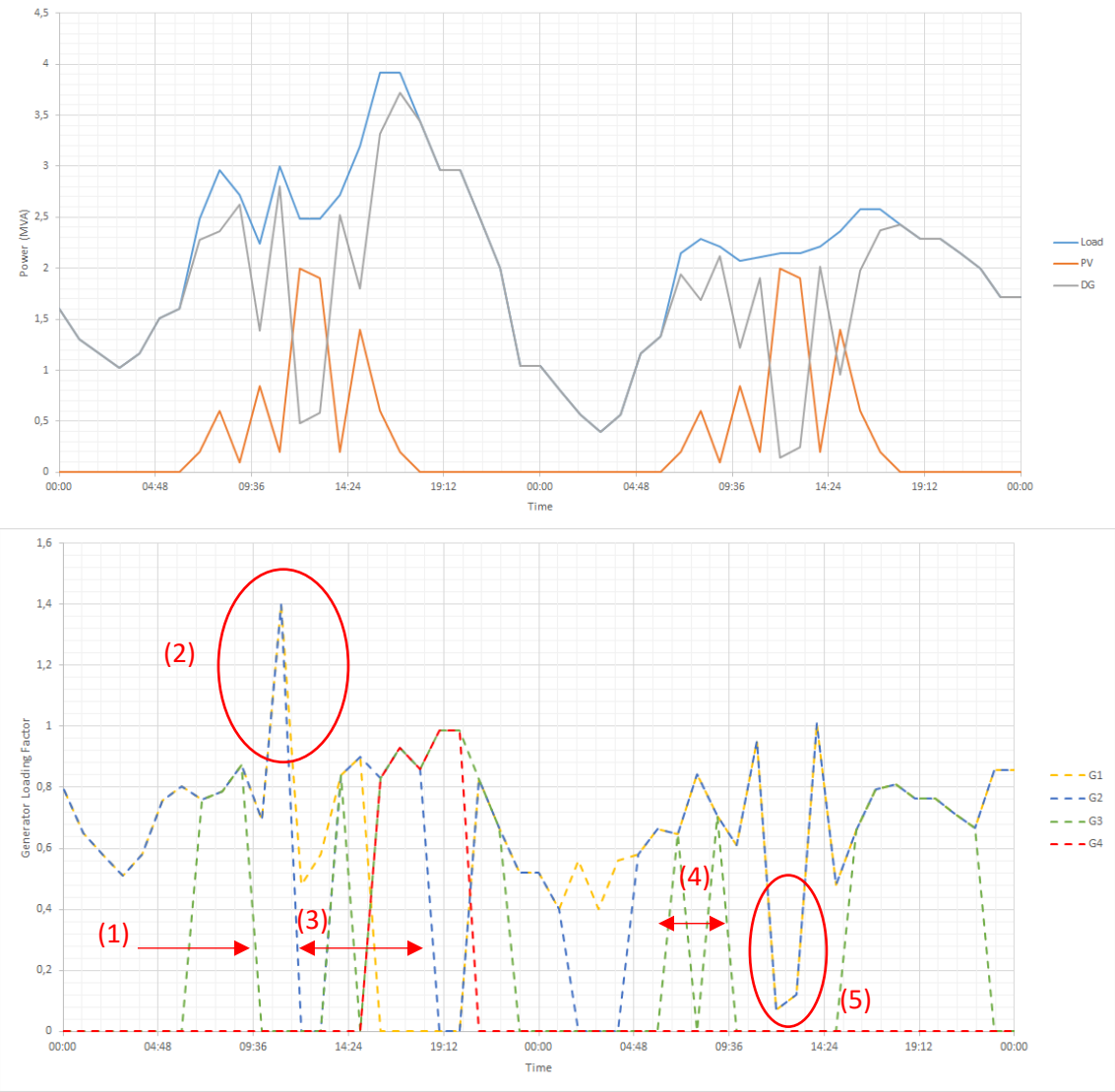


Figure 21. Last two intermittent days of Figure 20 top and generator contribution bottom for uncontrolled condition.

In Figure 21 several problems can be seen in the generator operation. Firstly at (1) generator three (Q3) is switched off as it is no longer required. This then results in generator one (Q1) and two (Q2) supplying 1.4 p.u. output, due to the inadequate spinning reserve capability of the system at (2). At (3) and (4) it is evident that the intermittency of the solar and the impact on load results in generators being switched off and on without consideration of minimum run time. Finally, at (5), it can be seen the generator loading of generator one (Q1) and two (Q2) drops to less than 10% which is well below the minimum 40% being used for this example.

Implementing a control scheme in the test environment, which replicates the performance of the physical controller in the system, progresses through a near real time load flow as depicted in Figure 22. Each loop of the load flow provides results to the simulated controller as described in Section 3.2.1. This in turn aims to manage the problems which arose in Figure 21 and issues operating setpoints to the generators and PV inverters to improve the operation of the site.

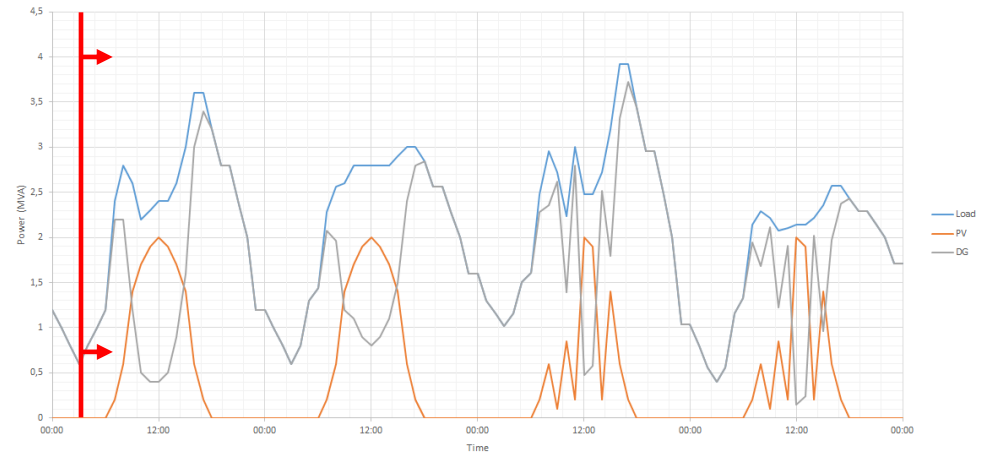
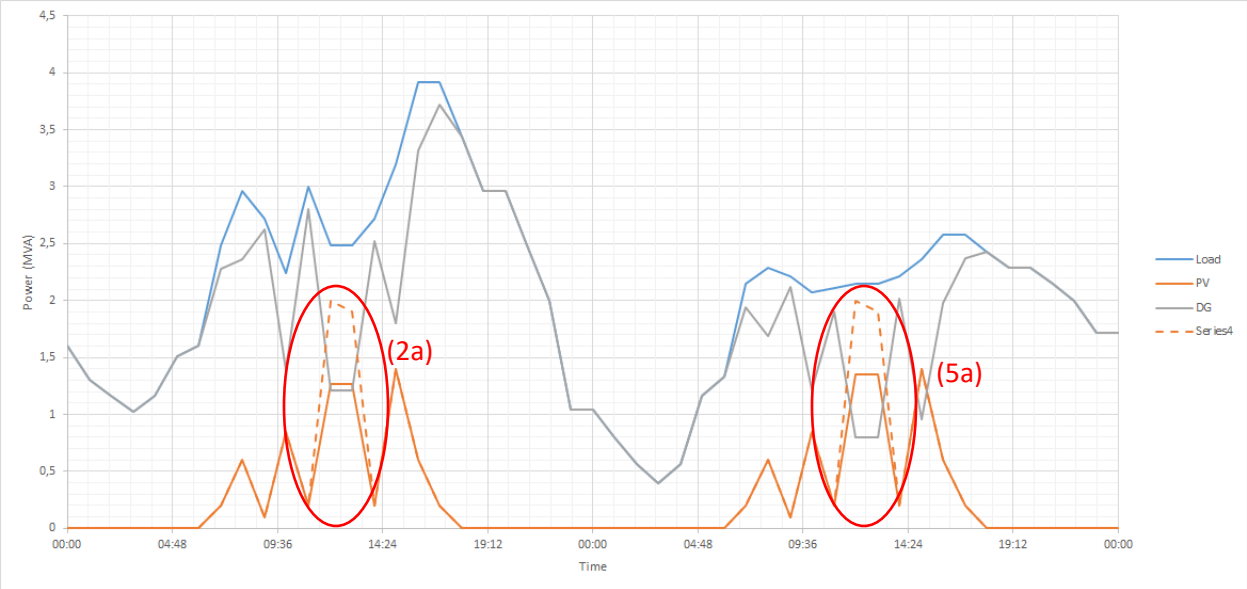


Figure 22. Example of real-time testing where the conditions presented by the load and solar profile are simulated over time as shown by the red line.

With the use of control, the results can be seen in Figure 23. What can now be seen at location (1) is that generator (Q3) three is kept online. This is because the controller has calculated the system has insufficient spinning reserve capability based on the PV output and pre-defined renewable coverage factors. This results in the system having adequate spinning reserve at (2) when there is a reduction in PV output. This does result in more generation online than in the uncontrolled case and therefore the controller is required to curtail the PV to manage the minimum load requirements for the online generators at (2a) and (2b). It can be seen in Figure 23 at point (3) and (4) that generators are not turned on and off constantly due to the solar intermittency as is the case in the uncontrolled example. This is because the scheduling is done by the controller that considers the minimum run time requirements of the generators. Lastly at (5a) the controller again curtails the PV output to avoid a breach of the minimum loading requirements of generators one (Q1) and two (Q2) at (5b).

This is a very basic description of some of the functionality. At a higher resolution test the controller also provides ramp rate limiting for step-load management, dynamic ratings of the generators to further avoid PV curtailment where possible, for further fuel savings.



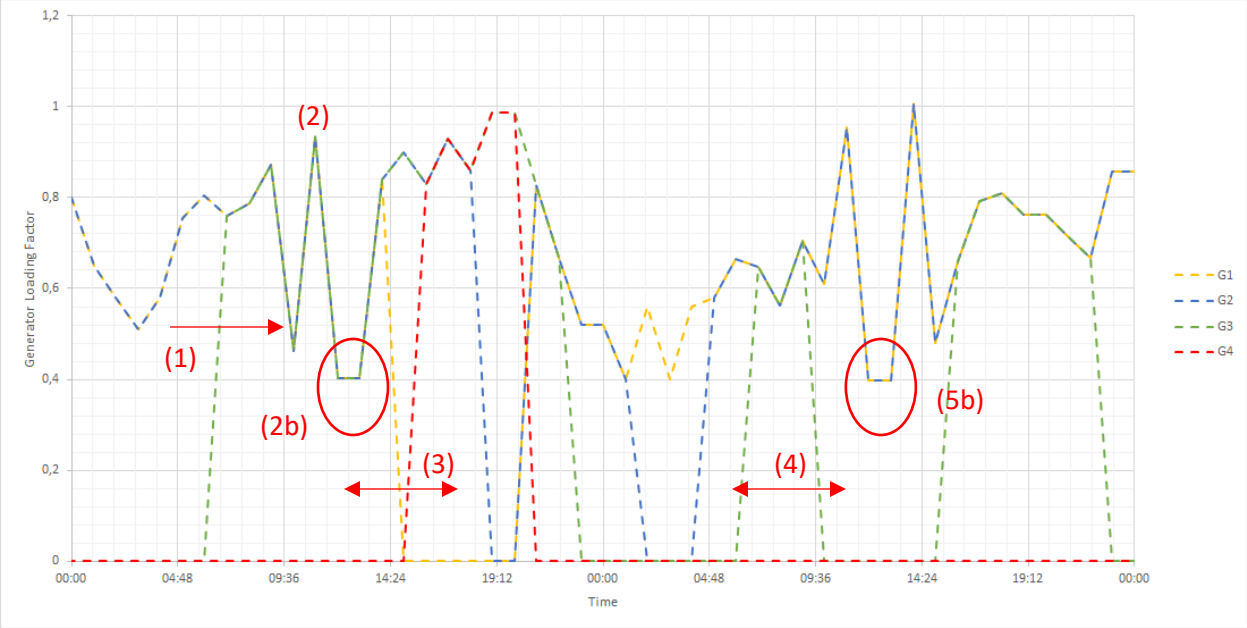


Figure 23. Last two intermittent days of Figure 20 top and generator contribution bottom for controlled condition.

The functionality of controllers are not limited, and over time additional functional layers can be added. For instance, weather data or cloud tracking can better inform the likelihood of a decrease in PV and more appropriately consider the level of spinning reserve to maintain.

This section demonstrates that observable and controllable PV with a low cost controller can allow greater penetrations of PV on isolated networks. In addition, these controllers can be accurately tested and configured prior to installation, with sophisticated modelling setups, to minimise costly time on site in remote areas.

3.3 BATTERY ENERGY STORAGE WHITE PAPER

Battery Energy Storage Systems (BESS) are the next opportunity for the electrical power industry. This is because of declining battery costs and the range of benefits they can provide, particularly with integrating intermittent renewable generation. A battery is ultimately a means of storing electrical energy by chemical means. The inverter and control system, the integration of the converter with the batteries and battery management system are what extracts the value from the battery storage system, for the benefit of the grid. The more capable and suitable for the particular application, the greater the benefit provided. This is not to say the batteries are not important, they are the foundation, but how the overall system is used is key.

The economics of battery energy storage is such that at present they are relatively expensive and leveraging numerous aspects rather than installing the system for one purpose is required and is referred to as 'value stacking'. This idea of value stacking is illustrated in Figure 24. It is important to understand what functionalities are possible, which complement and which conflict, to understand what functions can be performed in parallel to 'value stack' and also, what offers the most value to the power network.

The PowerStore™ Battery energy storage product is an advanced integrated energy storage solution that can be coupled with ABB's Microgrid Plus controller for over-arching control or integrated as a stand-alone energy storage product. The remainder of this section discusses some of the functionalities and approaches considered in the white paper.

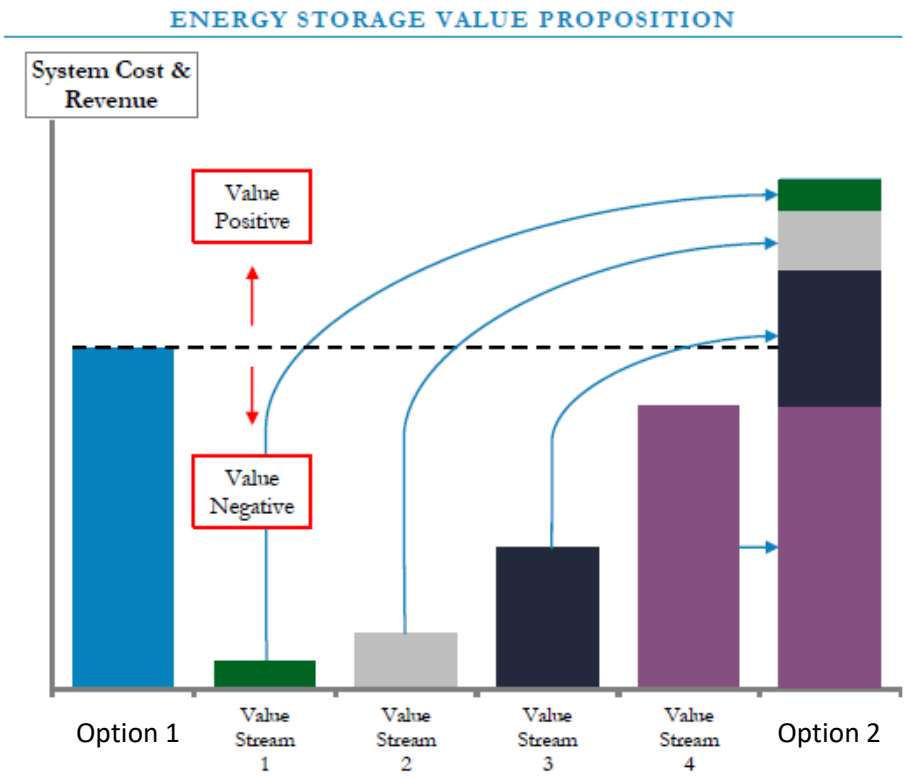


Figure 24. Concept of value stacking benefits. [36]

3.3.1 BESS Functionality

The costs of batteries are now at a stage where high power low energy applications are economically viable. This is supported by the recent National Grid Frequency Response Tender [37] and [36]. More energy intensive applications can also be viable but only on the networks that are significantly more expensive to maintain and operate.

Battery energy storage can provide many functions such as the “8 S” concept pioneered by ABB. The 8 S’s are a set of power system functions that energy storage can provide which range in power, energy and time and are:

1. Stabilising
2. Spinning reserve
3. STATCOM (static synchronous compensator)
4. Standalone operation
5. Smoothing
6. Shaving
7. Shifting
8. Seamless transfer

This is a useful overview of what functions energy storage can provide. These cover both on-grid and off-grid applications. Figure 25 shows a power versus energy plot of the 8’s battery energy storage functions.

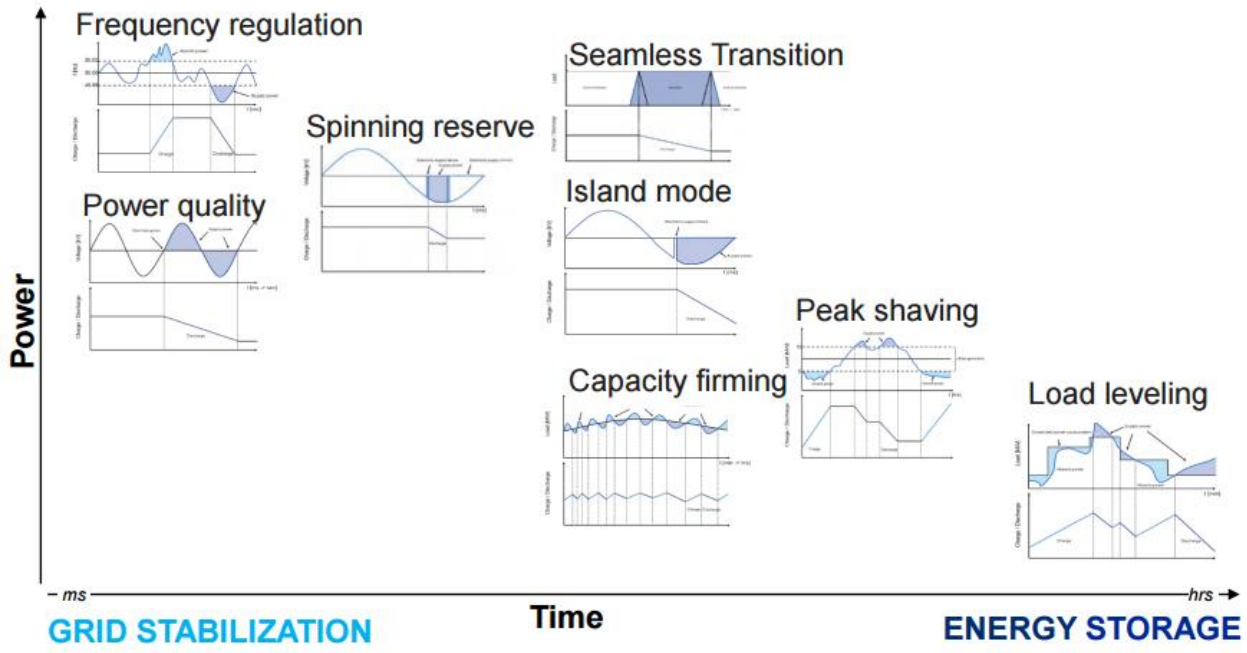


Figure 25. BESS applications with respect to time and power.

The term STATCOM is broadly used in this case and captures all reactive power services provided by the energy storage system. This was therefore expanded on in the white paper and the full range of reactive power services can be seen in Table 2. Table 2 summaries all the energy storage system functions considered in the white paper and whether they use real or reactive power. Some functions require a combination of real and reactive power but for simplicity the functions have been classified as below.

Table 2. Summary of battery energy storage functions.

Function		Real Power	Reactive Power
Grid Connected Operation			
1	Stabilise Frequency	✓	
2	Stabilise Voltage	✓	
3	Steady-State Voltage Support	✓	
4	Seamless Transfer	✓	
5	Shaving (Peak lopping)	✓	
6	Shifting (Energy Arbitrage)	✓	
7	Supply Power Factory Correction (STATCOM)		✓
8	Short Term Voltage Support (STATCOM)		✓
9	Steady-state Voltage Support (STATCOM)		✓
10	Sequence Compensation[2] (STATCOM)		✓
11	Screening and Sinking Harmonics[3] (STATCOM)		✓

At this point in time, the battery is the most expensive component so therefore cost can be assumed to be proportional to the energy required. Table 3 provides a comparison of the level of energy required for each function.

Table 3. BESS functions with respect to time frame and energy requirements.

Function		Time Frame	Energy Requirement
Grid Connected Operation			
1	Stabilise Frequency	ms	Low
2	Stabilise Voltage	ms	Low
3	Steady-State Voltage Support	sec - min	Medium
4	Seamless Transfer	hrs	Medium
5	Shaving	hrs	High
6	Shifting	hrs	High
7	Supply Power Factory Correction (STATCOM)	ms	None[4]
8	Short Term Voltage Support (STATCOM)	ms	None[4]
9	Steady-state Voltage Support (STATCOM)	sec - min	None[4]
10	Sequence Compensation (STATCOM)	ms	None[4]
11	Screening and Sinking Harmonics (STATCOM)	ms	None[4]

Value stacking as mentioned is important to extract all the value from BESS. Using BESS for one purpose will unlikely see it as an economically viable solution in the short term. However, BESS can offer a number of service that if set up correctly, can enable an economic investment. Some of these functions align whilst some are conflicting. The white paper considers how BESS can be applied in on-grid application and where value stacking can be done to achieve the most economical outcome.

[2] 'Sequence compensation' corrects voltage unbalance through negative sequence compensation
[3] 'Screen and sinking harmonics' can reduce the harmonic content in the line through active filtering
[4] A STATCOM requires some energy to supply the control system, auxiliary systems and losses. This level of power is insignificant with respect to the overall system and furthermore this energy can be sourced from the grid resulting in no drain on the batteries.

3.3.2 Economic Benefits

In addition to the technical aspects mentioned above there are three key economic aspects that energy storage systems can offer. These three 'S's' are:

1. Swift

BESS provides the opportunity to have resources online swiftly. Load forecasting plays a major role in determining the requirement for grid investment, yet it has always been complex and contained a level of uncertainty. Today, in the rapidly changing energy landscape, increasing DER, renewable energy policies, grid defection and changing power flows, load growth is very challenging to predict beyond the short term. The planning horizon of load forecasts however, often need to be longer term to match the long realisation time of conventional solutions. This can range from a few years at the low voltage and distribution level through to decades at the transmission level. BESS can be realised much quicker than conventional solutions. This makes it more agile in responding to sudden needs and allows major investment decisions in conventional infrastructure to be delayed until uncertainty in forecasts reduce.

2. Shiftable

BESS provides the opportunity to be relocated as required. This is a new concept for electricity infrastructure, but crucial when dealing with unclear forecasts and changes in policy, technology and behaviour within the energy system. Utilities are required to make costly decisions that depend on certain market conditions. When these conditions change, the viability of plans can also change. These large investments can become stranded, for many years, burdening rate payers. A key mechanism behind stranded assets in the power industry is that electrical infrastructure is typically static. With respect to power stations, substations, power lines and major network infrastructure, once built, it is not economical to remove, and they would remain stranded if location specific grid needs change, offering little to no value. BESS offers the possibility to recover, relocated and redeploy as conditions change, because of its modularity, and can continue providing value.

3. Scalable

BESS provides the opportunity to have resources online incrementally. Conventional utility solutions, with an operating life of 30 to 50 years, present a challenge for planners. Conventional solutions are only cost effective when oversized to match their long operating life. This results in a high upfront capital cost and low average utilisation over its lifetime. Quicker, incremental installations of BESS can be scaled up as required and provides a more targeted investment, providing benefit through the time value of money. This also protects against locking in a particular technology for many years, that may become obsolete, especially at the rate of change witnessed today.

3.3.3 Converter

The converter is the key technology when operating an energy storage system as it dictates the operation and function. Understanding the converter operation will also assist with what grid functions can be performed in parallel. A voltage source convertor (VSC), as the name suggests supplies a voltage. There are several advantages VSCs offer over current source converters (CSC), particularly in the battery energy storage application. Three of the most crucial are:

- decoupled active and reactive power control;
- capability to reverse power flows without changing voltage polarity; and
- capability to operate in weak and isolated power systems [38].

The continuous progress in the field of high-power fully controlled semiconductors has permitted the increasing penetration of power electronics in the power systems. It is anticipated that by 2030, 80% of all electricity will have been processed by power electronics. [39]

Understanding how power is transferred between the grid and a voltage source convertor is considered in Figure 26, where a coupling reactor connects the two.

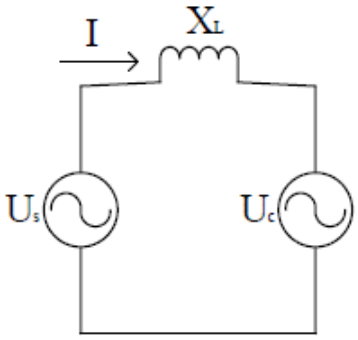


Figure 26. Diagram for how real and reactive power are delivered [40]

Now with Uc the converter voltage and Us the grid voltage, the real and reactive power can be described by:

$$P = \frac{U_c U_S \sin\delta}{X_L} \qquad \text{From [40]}$$

$$Q = \frac{(U_s cos\delta - U_C)}{X_L} U_C \qquad \text{From [40]}$$

In the above equations $U_S = U_S\angle 0$ is the AC system voltage and $U_c = U_c\angle\delta$ is the convertor voltage. The phase angle has a large influence on the active power whilst the convertor voltage has a large influence on the reactive power. Therefore, these can be controlled almost independently.

This describes the low level control and how the real and reactive power are exchanged between the device and the grid. Higher level control then manipulates what level of real and reactive power are used to achieve a particular function.

3.3.4 Required Functions for the Distribution Grid.

In accessing the importance of various functions for the power system, Figure 27 shows the order of criticality.

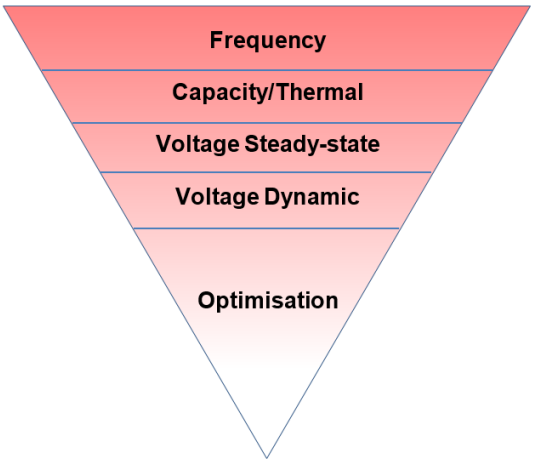


Figure 27. Diagram of importance of each power system aspect

Maintaining the power system frequency is fundamental to the power systems operation and stability. Without a stable frequency, the power system cannot operate. Capacity, from a network planning perspective, is the next aspect where the network is planned and reinforced based on the forecast load. Capacity limits are thermal in nature and therefore infrastructure and equipment typically have a short term or cyclic rating that allows overloading for short periods time. Capacity must be managed to ensure the power system can facilitate power flows and thermal constraints do not arise. Once the capacity on a network is managed effectively the next priority is steady-state voltage. The steady-state voltage typically must remain within ±5% of nominal around the world. There may be contingency or abnormal system conditions where it can deviate more than this temporarily but typically the voltage should be keep within this range to ensure adequate operation of all devices connected to the network. In addition to planning and managing the steady-state voltage, dynamic voltage variation need also be managed. Distorting loads were typically assessed at the time of connection application but ongoing validation may not always have been possible in the past due to limited network parameter visibility. Voltage sags, swells and flicker need to be managed to avoid the adverse effect they have on connected devices. Increased renewable generation intermittency on the network can create an increased level of voltage dynamics also, so the ability to managing these is important. Renewable integration can typically be achieved by managing the frequency, capacity, steady-state voltage and dynamic voltage impacts they cause.[5] This makes energy storage a valuable technology for renewable integration as it can assist with all of these parameters. Finally, some optimisation can be achieved such as energy shifting for energy arbitrage, reducing system losses or providing some other services that are not essential for effective power system operation. The value of any optimisation services should be considered with respect to reducing the battery life.

[5] Power system protection also needs consideration and this can be a limitation to renewable energy or DER integration.

3.3.5 Operating Philosophy

In designing the operating philosophy of a BESS, the system should manage these aspects in order of criticality. However, there is a somewhat inversely proportional relationship between the criticality and the rate of occurrence. Take peak load for example. Whilst the network is designed to manage peak load, the occurrence is very infrequent. A typical load duration curve can be seen in Figure 28. The amount of time the system operates at above 90% is approximately 2% of the time or 7.3 days a year. This can highlight why building conventional electrical infrastructure to solve a capacity constraint may not be the optimal solution. Equally though, it shows that installing energy storage for this sole purpose may underutilise the system. It may be beneficial during the time capacity is not a constraint to perform other functions. Figure 29 shows the somewhat inversely proportional relationship between the criticality of a power system parameter and its rate of occurrence.

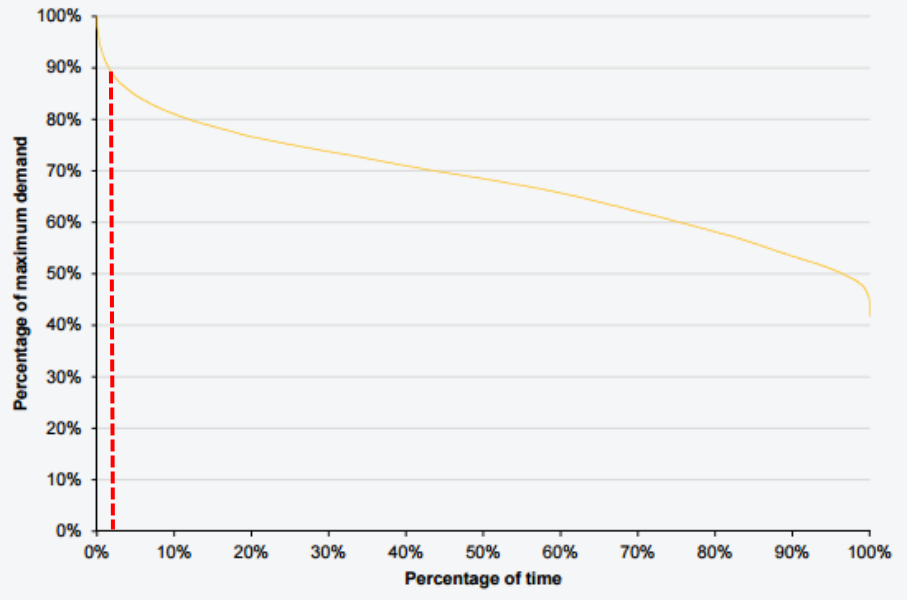


Figure 28. Typical load duration curve

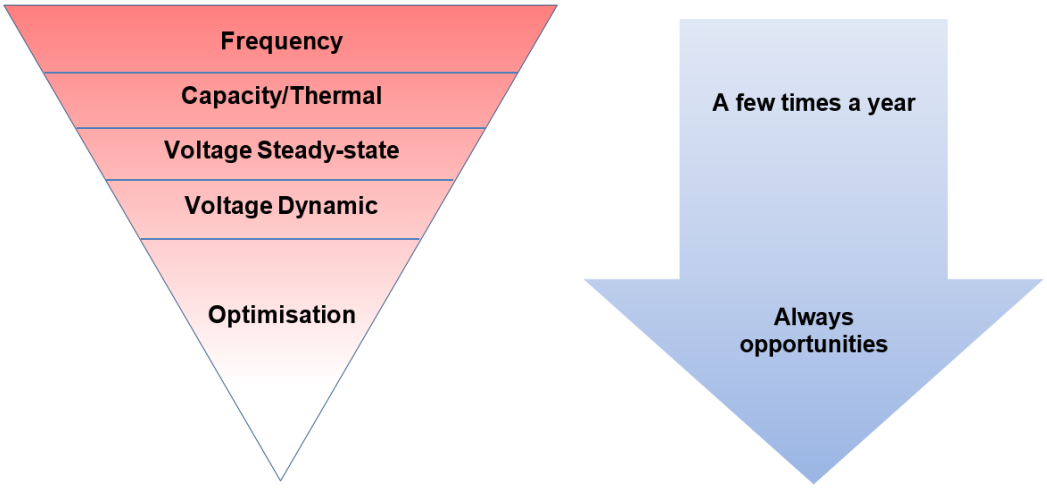


Figure 29. Diagram of importance of each power system aspect with respect to rate of occurrence

This provides context around the operating philosophy which will be discussed in the following section.

3.3.6 Operating Methodology

The operation of energy storage should ideally manage the power system aspects in order of criticality but in order to utilise the system fully, manage less critical aspects when possible. Figure 30 outlines a possible methodology for achieving this. It is important to note that it is not possible to de-couple all of these aspects. For example, injecting power to increase frequency will also reduce downstream load and increase voltage.

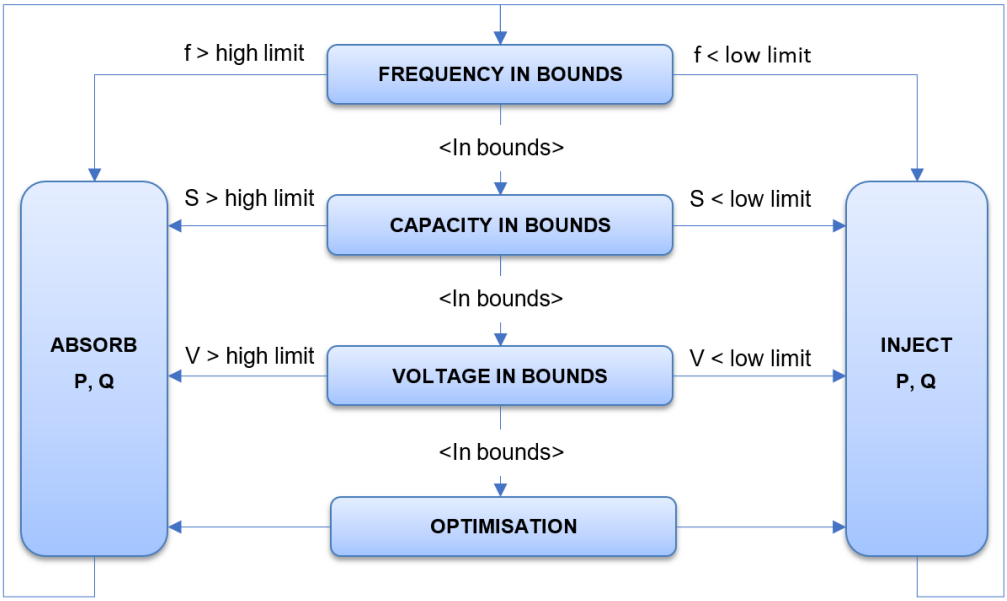


Figure 30. BESS control philosophy based of power system constraint importance.

Whilst Figure 30 is based on power system operation criticality, there is also a need to respond in an appropriate time frame to each parameter. Frequency response remains at the top as a response in the range of milliseconds is required to manage frequency. However, capacity need only be managed in the minutes to hours timeframe, depending on the magnitude, as the constraint is thermal in nature. Voltage on the other hand, like frequency may need to be managed in the millisecond time frame. The CBEMA curve in Figure 31 provides a guide on what short-term voltage variations are acceptable and could be used to define the limits to drive the short-term voltage response of the BESS. With this taken into account the approach described in Figure 30 could be modified to cater for the timeframe requirement to appropriately provide dynamic voltage support and capacity support as set out in Figure 32.

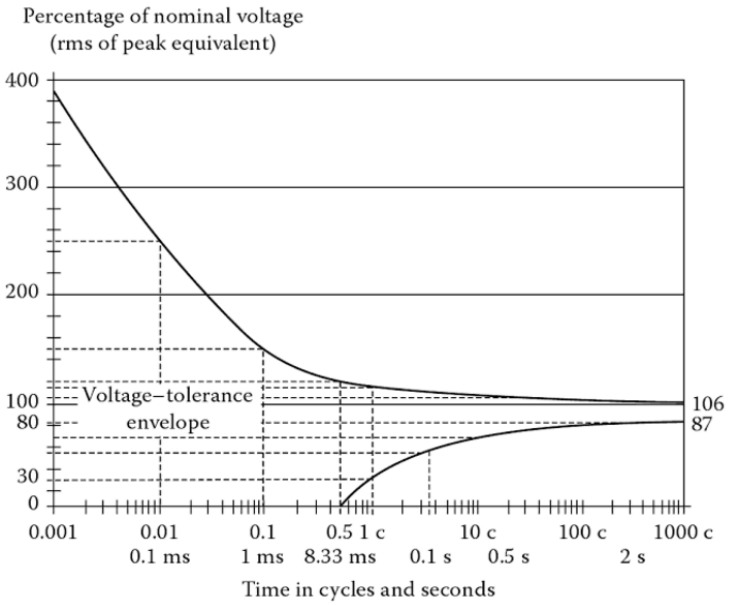


Figure 31. CBEMA Curve. [35]

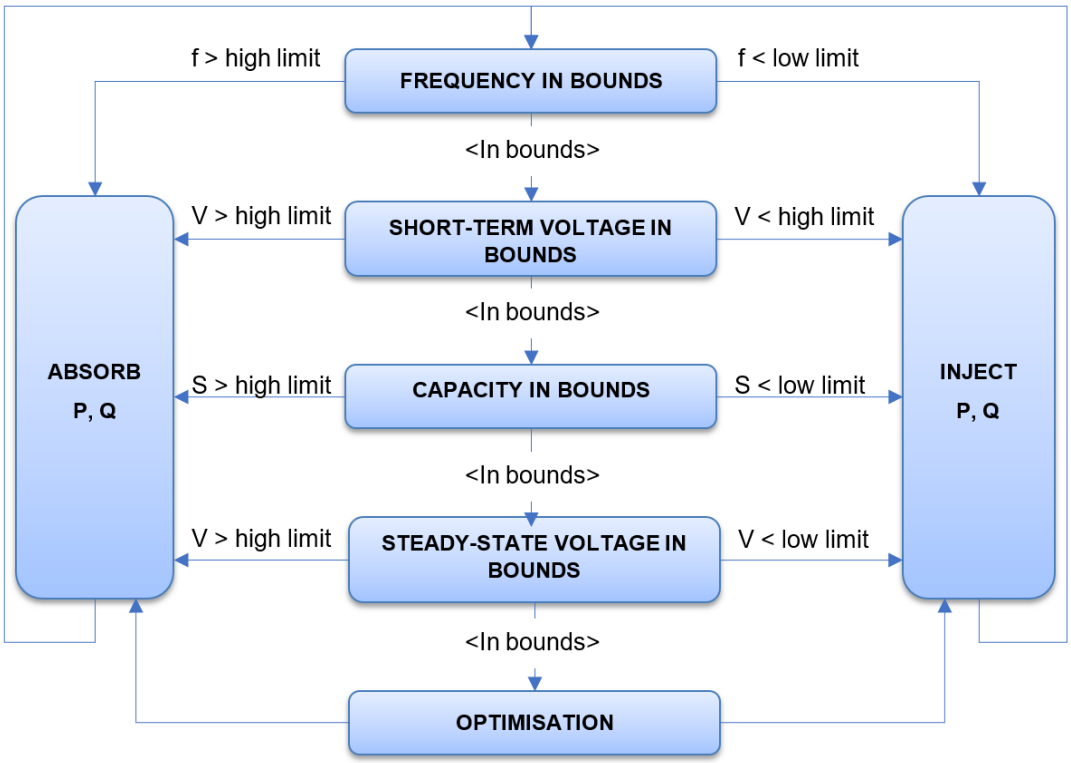


Figure 32. BESS control philosophy based of power system constraint importance and timeframe.

This provides background regarding the considerations and investigations conducted with respect to BESS and value stacking various functions. There remain more levels of control to manage these functions with respect to state of charge and how real and reactive power are delivered in a timely and meaningful way, with respect to the excursion of each parameter. These will be

considered in the ongoing work to help determine what functions are complimentary and which are conflicting.

3.3.7 Microgrid Applications

Whilst the focus of the BESS operation was on grid connected applications, it is important to mention the Virtual Generator Mode of the PowerStore™ Battery product. This mode, for off-grid applications, operates as a grid reference and mimics the behaviour of a physical generator to provide characteristics such as inertia, that are important to the power system's operation. Often it is assumed that new technology only reduces system inertia but by adopting controllers to operate in a similar fashion existing generation, it can assist the power system to operate. Frequency response on power systems is generally declining as renewable generation increases and traditional synchronous generation decreases. This lowers system inertia and the ability to provide necessary system response. BESS can assist with this developing problem. Figure 33 shows the Virtual Generator Mode for off grid applications, but on grid applications can also benefit from similar arrangements.

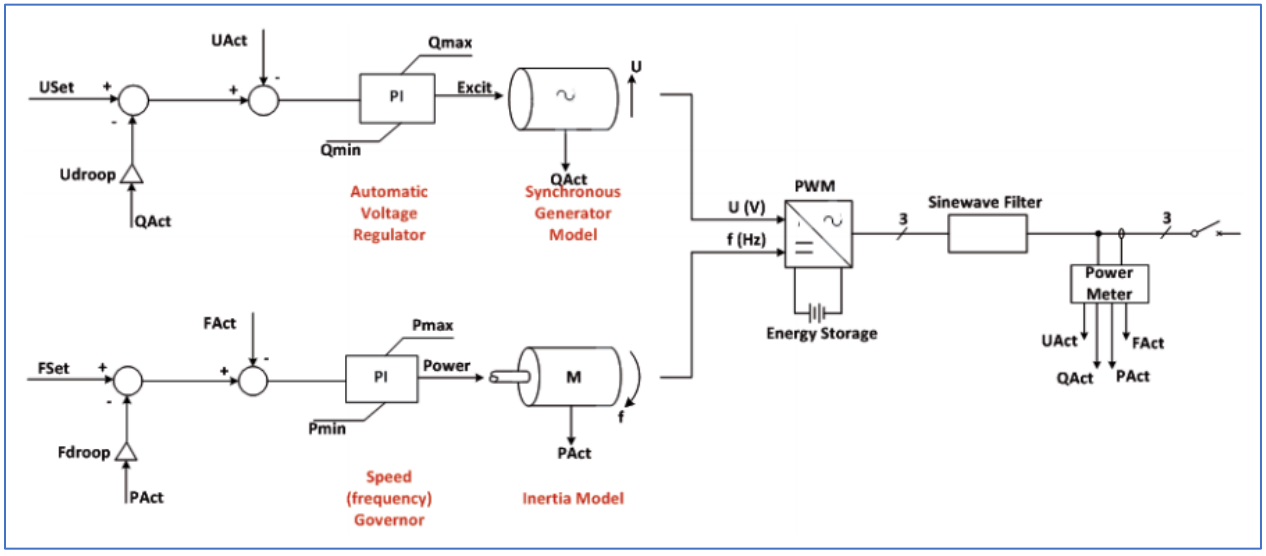


Figure 33 Virtual Generator Mode of the PowerStore™ Energy Storage System.

This white paper is ongoing with the intent to refer to ABB's stability tool, which focuses on the battery sizing for stability applications in off-grid situations and a battery aging tool which is fundamental to project planning. In general, for stability purposes, the amount of energy storage required is very low, and it is generally the 'C' rate of the battery that will determine the amount of energy storage, rather than the energy needs for stabilisation.

A colleague is also undertaking protection studies with respect to ABB's PowerStore™ Battery product. This is an important area to be understood. The PowerStore™ Battery produces a fault current of 2 p.u. for an extended period of time which allows for more effective integration than typical inverter based systems that produce a fault current similar to their rating. It is hoped this work can be referenced from the white paper to provide more in-depth detail with regard to protection.

4 OBSERVATIONS

4.1 ELECTRICITY AND PRICES

4.1.1 How Does Queensland Compare to Europe?

Comparing electricity prices provides a level of perspective. A direct comparison of Europe and Queensland, seen in Figure 34, shows that the cost of electricity is similar to countries of a comparable economic status and standard of living. There are several factors that aren't considered within this direct comparison that will be explored further below. However, in Figure 34 three countries of note are France, Germany and Denmark. France has a very low cost of electricity for a first world country and it is worth investigating the mechanisms behind this. Denmark is shown to have the highest price and a contribution at the CIGRE sessions from a member of a DSO in Denmark, mentioned that home energy storage was growing rapidly in the country due to high electricity costs. Whilst perhaps obvious, this reinforces that customers will respond to high prices by turning to alternatives. Final, Germany has always been a leader in the amount of DER integration within Europe, and is pursuing the Energiewende (energy transition) away from nuclear generation. Germany is therefore a useful comparison for Queensland with respect to DER penetration.

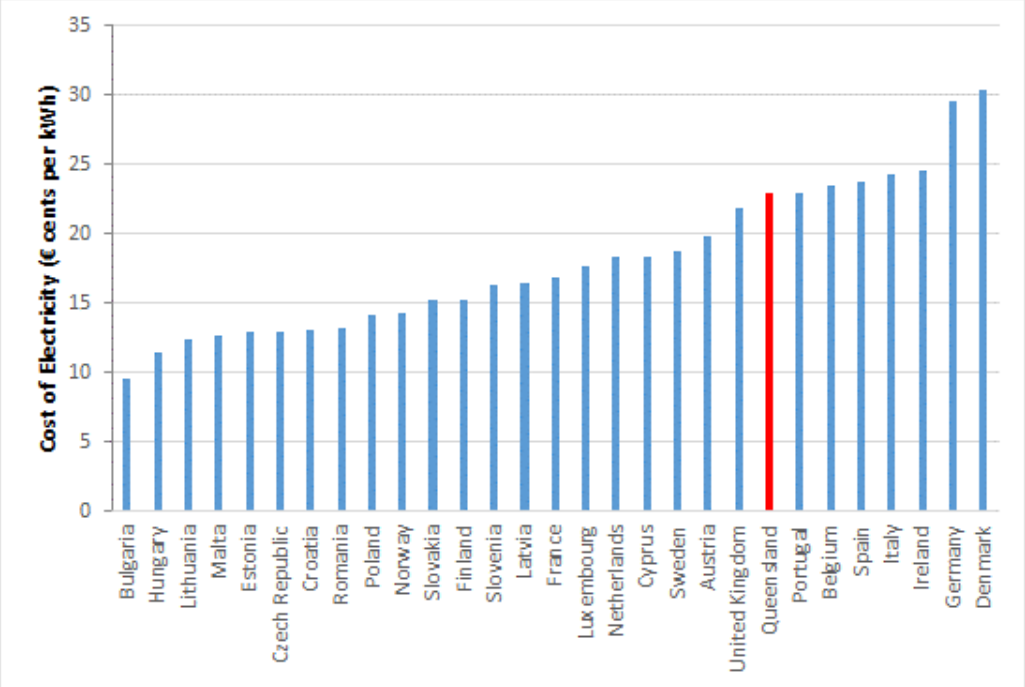


Figure 34. Comparison of European electricity prices with Queensland [41]

The cost of electricity in Queensland is shown as 22.87 euro cents. This value is based on the following assumptions.

1. Average customer usage in Queensland for 2015 was 4203kWh. [42]
2. In 2015 tariff 11 was 24.462c/kWh and 117.401cents/day. [43]
3. This equates to an annual bill of $1456.65 which is 34.6574cents/kWh.
4. An exchange rate of €0.66/$AU1.00.

Absolute cost is not a true reflection of electricity prices however, and it is important to consider the cost with respect to the cost of living and average wage. Figure 35 shows the average wage of the countries within Europe as well as Queensland.

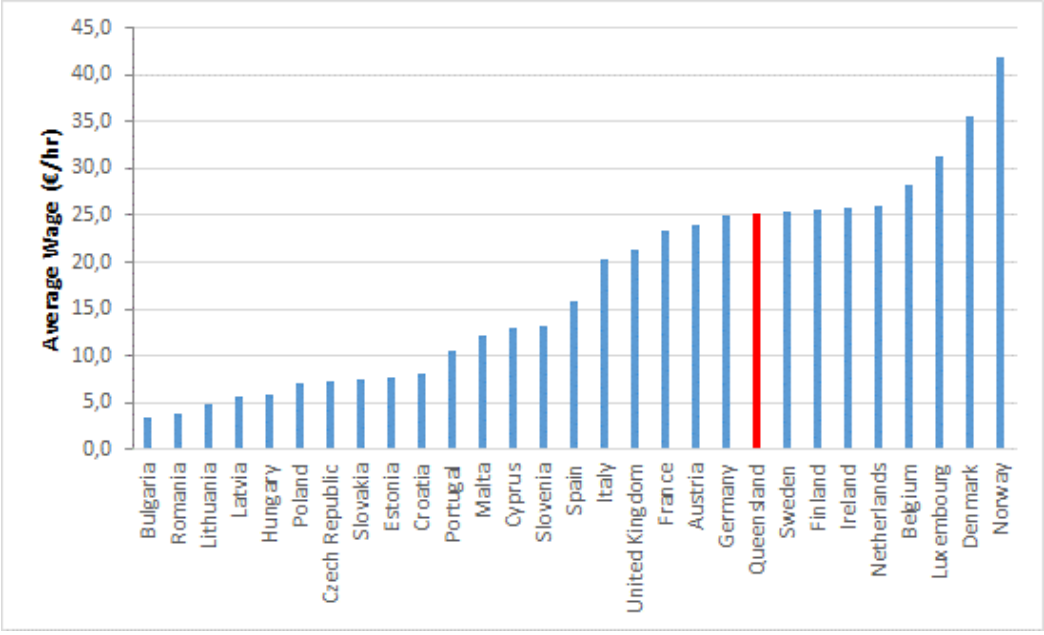


Figure 35. Comparison of average wages within Europe to Queensland [44, 45]

When both the average wage and cost of electricity are considered, a better perspective on electricity affordability can be gained. Figure 36 shows how many hours of labour are required, at the average hourly rate of that country, to purchase 100kWh of energy.

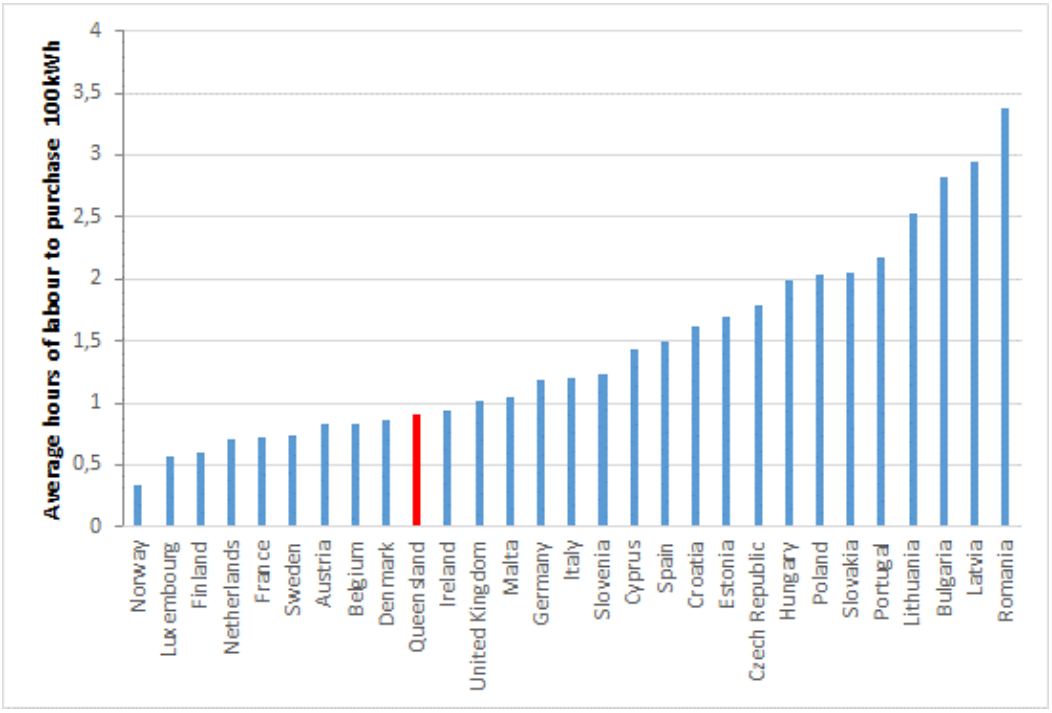


Figure 36. Comparison of European electricity prices with Queensland with respect to wages.

Whilst Queensland is towards the lower end in Figure 36, another aspect that influences the total cost of energy is how much is consumed. It can be seen in Figure 37 that Australia consumes more electricity than most European countries. Only Scandinavian countries use more and this may reflect extreme weather conditions and the need for heating, whereas Queensland requires more cooling than most European countries. In addition, European countries are more likely to have other sources of energy, such as gas, compared to Queensland.

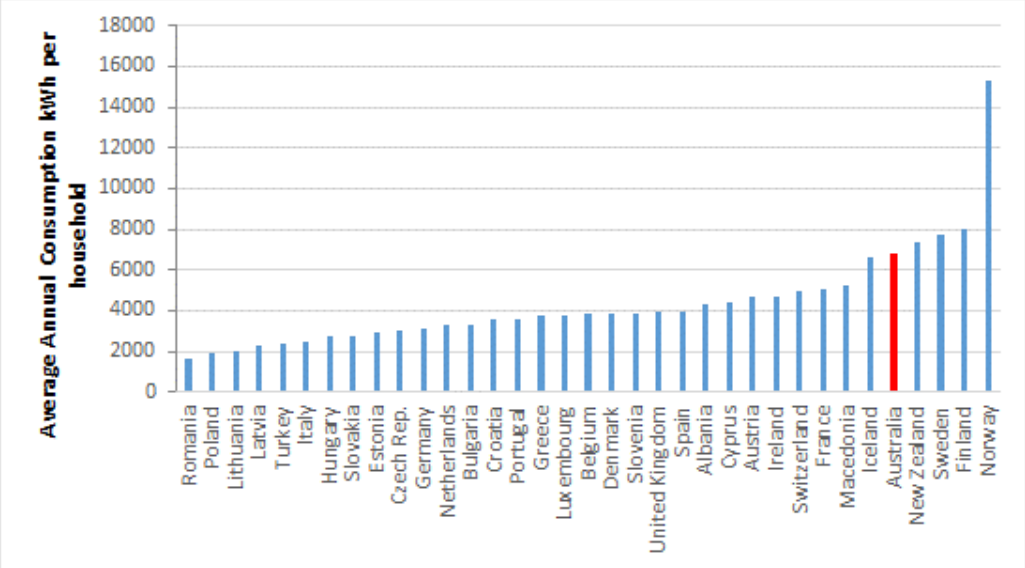


Figure 37 Comparison of average annual energy use around the world [46][6]

The level of infrastructure required to serve a customer influences the cost of providing electricity. Whilst a comparison with Italy is done in the next section, it has not been done at a European level. Figure 38 shows a comparison of Queensland to Europe to give an indication, and when considering the respective populations, it is clear Europe has a vastly denser network. Italy's population is approximately 15 times larger than Queensland's.

Figure 38. Comparison of the area of Queensland to Europe.

[6] Note the average annual energy use for Australia differs from the previous value use for Queensland, 4203kWh from [42] but it is useful for ranking Australia with respect to other countries.

My conclusions are electricity prices in Queensland are not higher than Europe, whilst this does not mean more cannot or should not be done to lower electricity prices. The cost is similar or favourable to countries with a similar standard of living and Queensland has some additional challenges such as distance, low customer density and extreme weather to manage.

I believe there is a problem with the preserved value of electricity in Queensland as many of the benefits a utility provides are not evident when a customer receives their electricity bill. Effort needs to be invested in highlighting the value the electricity grid provides but equally, it needs to evolve to offer value in areas customers now desire. Finally, Australia has higher electricity use compared to much of Europe which also adds to the perception of high costs, especially as most tariffs are heavily comprised of energy usage charges.

4.1.2 How Does Queensland Compare to Italy?

As a comparison of Queensland with Italy, Table 4 summaries some key statistics regarding the DSOs of Queensland and Italy.

Table 4. Comparison between Queensland DSO's and Italian DSO. [5, 47]

	Ergon	Energex	Queensland	Italy
Customers	733,000	1,400,000	2,133,000	31,423,623
Line Length (km)	160,000	52,000	212,000	1,105,216
Customers/Line Length (#/km)	4.58	26.92	10.06	28,43
Cost of electricity for average residential consumer ($AU/kWh)	0.347	0.347	0.347	0.368[7]

There are unique mechanisms in Italy to assist with managing the cost of supply, particularly for the distributer. By default, the connection to a dwelling is limited to 3 kW. To add perspective here, in 2015 the average sized inverter on Ergon Energy's network was 3.7 kVA. [5] So it can be assumed parts of Ergon Energy's network at times accepts more power than Italy's is typically designed to deliver. A customer in Italy may request a higher connection but will be placed on a more expensive tariff as seen in Appendix A. If demand exceeds 3 kW the supply trips, with some dwellings also having an alarm to alert the customer. Living in an apartment with this feature posed very little inconvenience. The few times the supply tripped was because I was not aware of the appliances I was using, as oppose to requiring that level of demand. This highlights the lack of customer feedback currently in electricity systems and the unintended result this can have on peak demand. Another mechanism in Italy is that central heating is controlled. Buildings are prohibited from using heating until the 1st of November in Genova, regardless of temperature. It is expected that households adhere to this rule also. There is no way to limit your use of portable heaters, connected to a GPO, but it is another restrictive measure imposed on customers to manage demand and energy efficiency.

With a significantly higher network density, limitations on the use of heating and a standard 3 kW connection limit, Italy's electricity prices are still higher than Queensland's. In Italy though, the price of electricity is not linear like Queensland, due to the progressive tariffs, which are discussed in the next section.

[7] 24.3 euro cents at a rate of 66 euro cents to the dollar.

4.2 ELECTRICITY TARIFFS

Whilst the average cost of electricity in Italy is described to be more expensive in the above section, the referenced document does not consider the Italian tariff structure completely. There has been substantial effort invested into progressive tariffs in Italy to assist with energy efficiency and the result is the tariffs are more cost reflective of network investment. This is fundamental to achieving cost effectiveness. Figure 39 shows a comparison of the standard Italian 3 kW connection tariff versus the Queensland's Tariff 11. It is evident that at an average Queensland household usage of 4203 kWh, the Italian tariff is more expensive. However, consumption is less in general in Italy, and there is a financial incentive to use less energy.

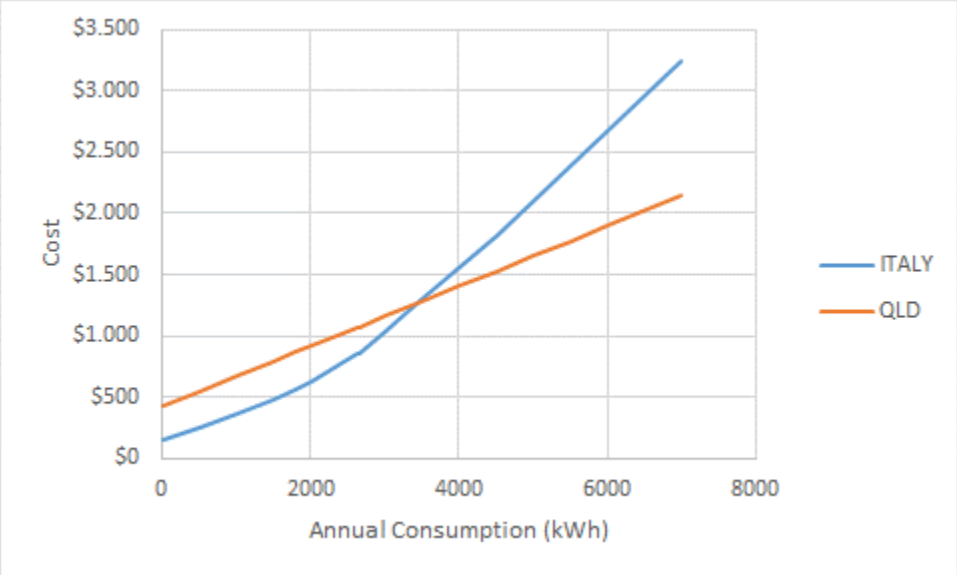


Figure 39. Comparison of Italian charges to Queensland charges with respect to consumption [42, 48].

There are four possible options in Italy, a connection less than 3 kW or more than 3 kW in combination with or without time of use metering. These can be seen in Appendix A. Table 5 shows the structure of the < 3 kW time of use tariff. If time of use metering is not in place, Fixed Energy Rate Time 1 and Fixed Energy Rate Time 2 are set at the same rate.

Table 5. Italian < 3 kW connection tariff, not including taxes [48]

Section	Components	Rate
Fixed Charge		€ / customer / month
Energy	Fixed Energy Rate Time 1	€ / kWh
	Fixed Energy Rate Time 2	€ / kWh
	Inclining Rate for energy transport	Rate for consumption up to 1800kWh Rate: consumption from 1801-2640 kWh Rate: consumption from 2641-4440 kWh Rate: consumption over 4440 kWh
Network Services	Fixed cost per month	€ / customer / month
	Demand Charge	€ / kW engaged / month
	Inclining Rate for energy transport	Rate for consumption up to 1800kWh Rate: consumption from 1801-2640 kWh Rate: consumption from 2641-4440 kWh Rate: consumption over 4440 kWh
	Inclining Rate for retail	Rate for consumption up to 1800kWh Rate: consumption from 1801-2640 kWh Rate: consumption from 2641-4440 kWh Rate: consumption over 4440 kWh

It can be seen in Table 5 that there is a fixed component, an energy component comprising a time mechanism and an inclining usage rate for energy. There is also a network services component comprised of a fixed cost, demand cost, another inclining energy cost and a retail cost. The sliding scale of cost for consumption offers a mechanism that can encourage energy efficiency and can be implemented with traditional energy metering. Allowing modest energy use to be cheaper and excessive energy use to be more expensive can assist low income earners and, in the absence of meters that can measure demand, have some effect on reducing peak demand.

A demand charge is very important for cost reflective pricing with peak demand being a primary driver of network investment. The application in Italy does not see the demand charge have a significant enough cost to have a meaningful effect on demand. However, with the physical 3 kW limit controlling demand it Italy, this is less important. In Queensland, a heavier weighted demand component could be adopted.

In considering cost reflective pricing, energy has little relevance to a distributer today. Connections to the grid, its ability to accept generation, meet peak demand and offer high reliability are all cost drivers for distributers. From a customer's perspective, high reliability, hosting capacity (ability to accept injection) and meeting their peak demand needs are of value. These aspects are perhaps better cost mechanisms in the future for distributers.

5 OTHER ASPECTS

This section covers other work and experience I gained during my time abroad but was not directly related to my placement at ABB.

5.1 46TH CIGRE SESSION PARIS

At the end of August I was fortunate enough to attend the 46th CIGRE session in Paris. To be being able to attend this conference, I would particularly like to thank Terry Killen and Denis Warburton from CIGRÉ Australia National Committee (ANC) who supported my attendance.

Founded in 1921, CIGRE, the Council on Large Electric Systems, is an international non-profit association that facilitates collaboration with experts from all around the world by sharing knowledge and cooperating to improve the electric power systems of today and tomorrow. [49] The CIGRE sessions are a biennial event held in Paris that allows utilities, academia, manufacturers, consultants and other members of the power industry to share challenges and work through study groups to help progress the power industry.

It was a very interesting week that not only covered areas I commonly deal with but it gave me a fantastic overview of the electricity industry as a whole, across many countries. Rarely is there a single conference that covers such a diverse range of areas. It showed me the interdependency between markets, regulation, generation, transmission and distribution and I believe better outcomes can be achieved by understanding challenges from all these perspectives and not just one or two.

The key themes were Microgrids and HVDC. Previous sessions had focused on HVDC but with the inclusion of discussions on Microgrids this year, I found it interesting that these are solutions at opposite ends of the spectrum to the same challenge, of integrating renewables. Communication and control technology today allows all resources within a power system to operate in a controlled and co-ordinated way. HVDC, leveraging off the improvement in power electronics, provide high power interconnections to strengthen the network and balance intermittency issues caused by renewable generation. This is a more conventional approach of building additional grid infrastructure.

The opening address was by Claudio Facchin where he discussed the ‘big shift’ in the electricity industry and featured some of the ABB projects that the research team in Genova were involved with. There was a substantial focus on renewable energy and not just the technical aspects but the impact on markets and business models. It was made clear why these needed to change although no recommendations were made. Regulation seems to be the main barrier for all countries in adopting innovative solutions.

With respect to my theme I will summarise my observations from two key areas, battery energy storage and integrating DER.

5.1.1 Battery Energy Storage

The price of energy storage is now cost effective for frequency regulation purposes on typical electricity networks. This was supported by the Nation Grid frequency response tender [37] which included all battery storage. This high power low energy application is a result of the power

electronics component being relatively cheap with respect to the batteries. [36] also compiled an energy storage comparison that suggests Li-ion batteries for frequency regulation are currently competitive.

It was discussed that while it is inevitable that battery energy storage applications will increase on the power system, if the system becomes highly reliant on renewables there remains a problem covering generation gaps where several hours to days of storage is required. Events such as the solar eclipse in Europe, which was discussed in a separate talk, saw a 19 GW decrease in generation and highlighted that significant reserves that were required for that day, which was well forecast.

Apart from frequency response, many energy storage suppliers were targeting isolated networks for diesel fuel saving applications. The importance of valuing stacking was present in many presentations and I discussed this in Section 3.3.

Some general points were:

- Very little mention of home energy storage but CIGRE has developed from a generation and transmission heritage which may explain the limited discussion in this space.
- A DSO from Denmark did mentioned they have significant home battery energy storage systems connected due to high tax on electricity. They don't have visibility of these systems suggesting this is happening with little standards or audit process yet in place. This highlights possible grid defection if grid prices are too high.
- Battery energy storage is recognised as cost effective for auxiliary services now and smoothing and daily renewable integration in the short to medium term. It remains unclear how to move beyond this stage and replace fossil fuels for large scale reserves.
- Several presentations highlighted the importance energy storage can offer
- It was highlighted in many presentations that there isn't one solution but a combination are required in this rapidly changing energy landscape

5.1.2 Voltage Regulation and Distributed PV

Some general points on voltage regulation and managing DER integration were:

- In Germany 95% of PV problems are addressed by reducing the OLTC during the day.
- In Italy, this approach has also been found to be the most effective but care is required where feeders have different load profile characteristics. I.e. a residential feeder with a lot of PV and a commercial feeder with low PV supplied from the same OLTC.
- Several countries are investigating and trialling dynamic reactive compensation to manage voltage. This was primarily with smart inverters and not STATCOMs.
- Concerns were raised about where the reactive power for smart inverters will be sourced with the contribution of traditional power stations diminishing.
- Throughout Germany it is generally accepted that curtailing distributed solar is acceptable up to 3% of the time.
- Observability and controllability of distributed PV is poor and is a problem that will likely remain.
- The European solar eclipse highlighted challenges regarding the need for large scale fossil fuel reserves and the problems with unobservable and uncontrollable PV.

- Germany utilises reference PV installations to get an indication of the overall PV production, which was helpful for their preparations for the solar eclipse in Europe.

5.1.3 Other Aspects at CIGRE

Apart from the general sessions I as was able to be involved with the Next Generation Network (NGN) and young members' booth, encouraging young professions to join CIGRE. I attended the C6 Working Group, distribution systems and dispersed generation and lastly, I was able to visit an inner city GIS Parisian Zone Substation, which provided a contrast to the substations I'd previously seen in regional Queensland.

The opportunity to meet and work with other young members from around the world as well as working group members from academia, utilities and manufacturers was invaluable. At a time when technology and the energy landscape is changing so fast, it is impossible to stay up to date with each aspect alone. The professional network CIGRE Paris provided me access to is extremely valuable, for both finding out information during the week and in the time since.

Lastly, most of the young member events, the information booth and visit to a GIS substation in Paris, was organised by the Australian group, the most involved of any country this year. These were all Ergon and Energex employees that attended through different mechanisms. I think this highlights the passion and drive of young Queensland engineers in a global context and is a great achievement. These young Queensland engineers can be seen in Figure 40.

Figure 40. Stephen, Beer, Emma, Alex, Matt and Tara-Lee from Ergon and Energex at the Paris CIGRE sessions.

5.2 EUROPEAN UTILITIES WEEK 2016 'INITIATE PROGRAM'

In November I am attending European Utilities Week after I successfully applied for a young engineers' program called 'Initiate'. I will discuss this upcoming experience in my next report. However, one issue which was discussed as part of the application process was how Europe can reach their renewable energy targets. As seen at the CIGRE sessions, stronger interconnection is a means of connecting more renewables in Europe. Understanding some of the interconnection projects in Europe, and some of the challenges, made me reflect on Australia, especially with the recent blackout in South Australia.

Australia is a large country and comparable in size to the European continent. Interconnection can help leverage different renewable resources in different regions and balance instabilities. Europe however is made up of many countries, cultures, varying living standards, governments, expectations and economies. The purpose of the EU targets is to achieve a level of co-ordination between the countries and I found this analogous of Australia and the states.

Subsidies are now seen as a major barrier to renewables in Europe because there is a need to look beyond countries to regions. A problem for example is the Danish Government subsidising renewables when this electricity is generally exported at a wholesale market price to Scandinavia or Germany. Danish tax payers are therefore disadvantaged for the benefit of these other countries.

Another area is energy security. For example, the UK consistently draws power from France to meet its energy needs. [50] This connection is also utilised for frequency response and helps satisfy the technical needs of operating the British network. This is a sound technical and economic solution, however at a country to country level there can be concerns about energy security. Events such as Brexit also highlight the political situation can change drastically. The UK have now approved Hinkley Point C nuclear power station. [51]

Australia has a simpler environment to leverage interconnection for the purposes of increasing renewables. Whilst Europe is becoming more interconnected, the various aspects mentioned above all pose non-technical barriers to both the planning and operation of interconnection. Australia is fortunate that whilst states vary to a degree, they are all part the same country with similar standards of living, economies, tax system and energy security is not considered an issue between states. Cooperation and coordination should therefore be simpler to facilitate increased levels of renewables within Australia.

6 LESSONS LEARNED & RECOMMENDATIONS

In assessing the work undertaken to date and some of the lessons learned with respect to my research topic, I have presented the following points below.

6.1 QUEENSLAND HAS AN OPPORTUNITY TO BE A LEADER

PowerCorp were purchased by ABB in 2011 because of the unique expertise they had gained and applied in managing remote mini-grids and integrating renewable generation. Darwin is now one of the main global research and development centres for microgrids within ABB. Queensland has an opportunity to be a leader in supplying power to tropical islands, particularly in the Asia-Pacific region. Few regions are positioned as well as Queensland, with its economic strength, skilled resources and geography, if this strategy was pursued. This could be a valuable revenue stream for Queensland's utilities if relevant regulatory challenges are managed.

With respect to mainland Queensland, it already leads the world in the amount of rooftop solar per capita along with South Australia. The 'innovation dilemma' in Australia receives substantial attention and at a time following the mining boom there is an opportunity to capitalise on Queensland's climate, expertise and need to innovate to manage its unique, vast and sparsely populated grid. It is evident by the fact many of ABB's reference sites are located in Australia that Australia has the right conditions to benefit significantly from these new technologies. By embracing renewables and modernising the grid, it can not only assist Australia, but establish an industry that can lead other parts of the world as they transition to a low carbon future.

6.2 INCREASING PV IN ISOLATED POWER NETWORKS

There are two mechanisms to increase the level of PV beyond modest levels of peak penetration in isolated power networks. These are:

1. Curtail PV as appropriate if observable and controllable; and/or
2. Utilise energy storage for stability purposes.

Firstly, curtailing observable and controllable PV when necessary, as determined by a controller such as PVD, is the cheapest method of increasing PV penetration currently. This takes advantage of the dynamic nature of electricity systems. Static planning assessments that set PV connection quotas based on light load and or peak renewable generation output, which is a snap shot in time, limit PV penetration. For this reason, controllers such as PVD can assist in increasing the contribution of PV in isolated sites around Queensland. Whilst other challenges exist in some cases, particularly on islands where there can be limited space for controllable solar, these control systems can help lift solar penetration in a very cost effective way.

A key problem for Queensland and its isolated networks are that distributed PV is unobservable. In Germany, utilities utilise reference PV sites that provide information to indicate the output of unobservable and uncontrollable rooftop PV. There may be opportunities to investigate where partially observable and controllable PV can be used on isolated networks to indicate the likely total PV generation. Understanding the co-incidence and similarities between the observable and unobservable PV at each site, may assist in managing higher levels of PV. The controllable PV can be over curtailed in such situations to compensate for the uncontrolled PV.

If the PV is not observable, frequency and voltage deviations provide the mechanism to observe the PV behaviour. This signal can drive the charging and discharging of stabilising storage.

Through working with ABB and their energy storage sizing tool for frequency stabilisation in mini-grids, it is evident how little storage is required to facilitate a marked increase in PV penetration. This is re-enforced in the context of Marble Bar where the energy storage mechanism is a flywheel. A flywheel has high power and very low energy capability. In the case of Marble Bar, full output for a maximum of 30 seconds. These low energy applications are already economical for battery energy storage as reflected by [36] and [37]. The two key barriers to storage for stability purposes are; high mobilisation and on site costs and battery charge/discharge limitations.

Firstly, utilities need to work closely with manufacturers to get standardised, packaged storage solutions that can be effectively transported to remote locations and installed swiftly on site. Better outcomes can be achieved through collaboration. In my experience suppliers have great capability but don't always understand the finer details required to extract the full value. Utilities that understand the finer detail, can make assumptions as to what the solution they pursue should be and how it should operate, potentially underestimating what the supplier can provide.

At this point in time the C rate of batteries are a limitation for high power applications such as stabilisation. This will require more batteries to be installed than is required for the purposes of stability alone. This makes utilising it for other applications important as discussed in Section 3.3. However, even with this limitation, battery systems are becoming economic today in similar applications as discussed. This trend will only continue as battery prices reduce and/or C rates can be increased.

It is recommended that an assessment of the amount of storage for stabilisation is considered for each isolated site in Queensland, given relatively small systems can facilitate reasonable increases in PV. This can importantly be unobservable and uncontrollable solar PV distributed on precious rooftop space. It is likely many sites require less storage than assumed to facilitate reasonable increases in distributed PV.

6.3 CHARACTERISATION OF INTERMITTENCY

A controller offers flexibility to manage the system with different levels of risk. For example, a 100% loss of solar can be considered for the preservation of spinning reserve or a 50% loss can be anticipated to save more diesel (have less spinning reserve) but with more risk. It is important to characterise intermittency to ensure systems are not operated over or under conservatively. In addition, defining acceptable levels of risk is important as all aspects of the power system are designed based on risk. Defining realistic intermittency levels to anticipate and acceptable outage rates caused by intermittency is important to achieve a balance between risk and fuel savings.

6.4 ENERGY STORAGE REPLICATING SYNCHRONOUS MACHINES

My experience with the PowerStore^{TM} Battery product has highlighted that battery storage is not only offering important services to the grid but now minimising its integration challenges. Moving from synchronous generation to inverter based generation is fundamentally changing the power system. The PowerStore^{TM} Battery, by mimicking synchronous machines is important for maintaining system inertia. Another area that has posed integration challenges for energy storage in the past has been with existing protection systems. Many inverter based systems provide a minimum fault current, in the order of 1.1 p.u., as they are current limited. This can be challenging for existing protection schemes to distinguish between normal and fault conditions. The PowerStore^{TM} Battery provides a 2 p.u. fault current for an extended period, not just a pulse like

synchronous generation, which can greatly assist with managing system protection and integrating inverter based systems.

6.5 SOPHISTICATED MODELLING CAN BE LEVERAGED

Sophisticated modelling packages today offer the ability to pre-configure and test solutions prior to installation and incurring on-site costs. This testing can now include the physical devices through hardware-in-the-loop testing setups. Such testing offers additional benefit in the cases sites are remote and costly to access. It is therefore recommended that such platforms, through collaboration with appropriate manufacturers and providers are utilised in the future to avoid work and time on-site where possible.

6.6 COST AND PRICING

With respect to electricity prices, Queensland is not more expensive than similar countries in Europe. However, there are several aspects that could assist with reducing the increase in cost for consumers in the future. These are:

- Consider an inclining consumption pricing structure as this can be achieved with existing energy metering. This can help low income earners and will have some effect on peak demand in lieu of demand metering and tariffs.
- Consider tariffs that aren't energy based, or energy is not a major component.

In considering cost reflective pricing, energy has little relevance to a distributer today. Connections to the grid, its ability to accept generation, meeting peak demand and offering high reliability are all cost drivers for distributers. From a customer's perspective, this is also what is of value. High reliability, hosting capacity for their DER (ability to accept injection) and meeting their peak demand without restriction. Therefore, these may be better cost mechanisms in the future. An energy component should be included to ensure energy efficiency and for generators whom energy is a very important measure, but it does not need to be a major component for distributers.

6.7 SELL THE VALUE OF THE GRID

Finally, within electricity industry, there seems to be a consensus the best outcome for the future power system is a combination of the existing electricity grid and DER. This can facilitate a transactive electricity system and maximise the benefits both DER and the grid can offer. The grid defection case is considered sub-optimal. However, history is full of examples where the optimal solution does not prevail. There is a risk not enough is done to secure the electricity grid's future by assuming everyone is aware the grid forms part of the optimal energy system. The energy industry is best placed and well informed to guide this transition for the good of the wider community, who do not always have a holistic understanding. The value the grid provides needs to be conveyed better and regulations and markets need to evolve quickly to enhance DER, so customers are encouraged to work with the grid, not against it. DER in conjunction with the grid is the optimal outcome for everyone, and the electricity industry has a responsibility to ensure this is realised, not for the industry's future viability, but to ensure everyone can benefit.

7 FUTURE WORK

I will continue working at ABB, Italy until the 9th of December. During this time, I will work further on the energy storage white paper. I am currently working with DIgSILENT Power Factory to model and verify PV Plant Controllers and inverters for grid integration and utilisation for grid services. This is specifically testing the system against grid codes and the ability to utilise the inverters in various modes to provide frequency support to the grid, over frequency response by curtailing output, and utilising the inverter for reactive power for voltage, power factor and stability purposes. Conventionally, generation would connect at the transmission level and gaining experience at the distribution level is important as more renewable plants connect to the distribution system in Queensland. In order to provide cost effective connections, it is important to utilise grid services these PV power plants can offer.

In addition to the white paper, as mentioned in Section 3.3, a colleague has performed studies on the fault performance of string and centralised inverters, both with photovoltaics and battery energy storage as the source. Protection is a fundamental area in operating a power system safely and effectively and a better understanding of the fault performance of inverter based systems on the network will assist in their appropriate and effective adoption. I hope to reference this work in the white paper and learn and share some of the outcomes.

I will also attend European Utilities Weeks 2016 in November which will provide perspective on the challenges faced by European system operators and the approaches they are taking. It will also be a very good networking opportunity and chance to see some of the technical solutions vendors are offering to assist modern utilities.

Finally, I have also been trying to finalise a position in North America from January to June 2017. This has been very challenging, with several setbacks but I hope to finalise this shortly.

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APPENDIX A – ITALIAN ELECTRICITY TARIFFS

No time of use

Component			< 3kW		> 3kW	
Fixed	Fixed quote For each month of the quarter	€ / customer / month	2.365300		3.418600	
Energy	Energy	€ / kWh	0.067640		0.067640	
		dispatching component (variable part):				
	1st installment: consumption up to 1800kWh	€ / kWh	0.001640		NA	
	2nd echelon: consumption from 1801 kWh to 2640 kWh	€ / kWh	0.009760		NA	
	3rd installment: consumption from 2641 kWh to 4440 kWh	€ / kWh	0.021340		NA	
	4th echelon: consumption over 4440 kWh	€ / kWh	0.021340		NA	
Network Services	Fixed quote	€ / customer / month	1.200100		1.609100	
	Access Price	€ / kW engaged / month	0.838000		1.807500	
			Transport Expense	Retail Expense	Transport Expense	Retail Expense
	1st installment: consumption up to 1800kWh	€ / kWh	0.007160	0.039272	0.026170	0.082312
	2nd echelon: consumption from 1801 kWh to 2640 kWh	€ / kWh	0.032660	0.057612	0.042590	0.082312
	3rd installment: consumption from 2641 kWh to 4440 kWh	€ / kWh	0.069080	0.082312	0.042590	0.082312
	4th echelon: consumption over 4440 kWh	€ / kWh	0.069080	0.082312	0.042590	0.082312

Time of use.

Component			< 3kW		> 3kW	
Fixed	Fixed quote For each month of the quarter	€ / customer / month	2.365300		3.418600	
Energy	Energy in F1	€ / kWh	0.071490		0.071490	
	Energy in F23	€ / kWh	0.065730		0.065730	
		dispatching component (variable part):				
	1st installment: consumption up to 1800kWh	€ / kWh	0.001640		NA	
	2nd echelon: consumption from 1801 kWh to 2640 kWh	€ / kWh	0.009760		NA	
	3rd installment: consumption from 2641 kWh to 4440 kWh	€ / kWh	0.021340		NA	
	4th echelon: consumption over 4440 kWh	€ / kWh	0.021340		NA	
Network Services	Fixed quote	€ / customer / month	1.200100		1.609100	
	Access Price	€ / kW engaged / month	NA		1.807500	
			Transport Expense	Retail Expense	Transport Expense	Retail Expense
	1st installment: consumption up to 1800kWh	€ / kWh	0.007160	0.039272	0.026170	0.082312
	2nd echelon: consumption from 1801 kWh to 2640 kWh	€ / kWh	0.032660	0.057612	0.042590	0.082312
	3rd installment: consumption from 2641 kWh to 4440 kWh	€ / kWh	0.069080	0.082312	0.042590	0.082312
	4th echelon: consumption over 4440 kWh	€ / kWh	0.069080	0.082312	0.042590	0.082312